

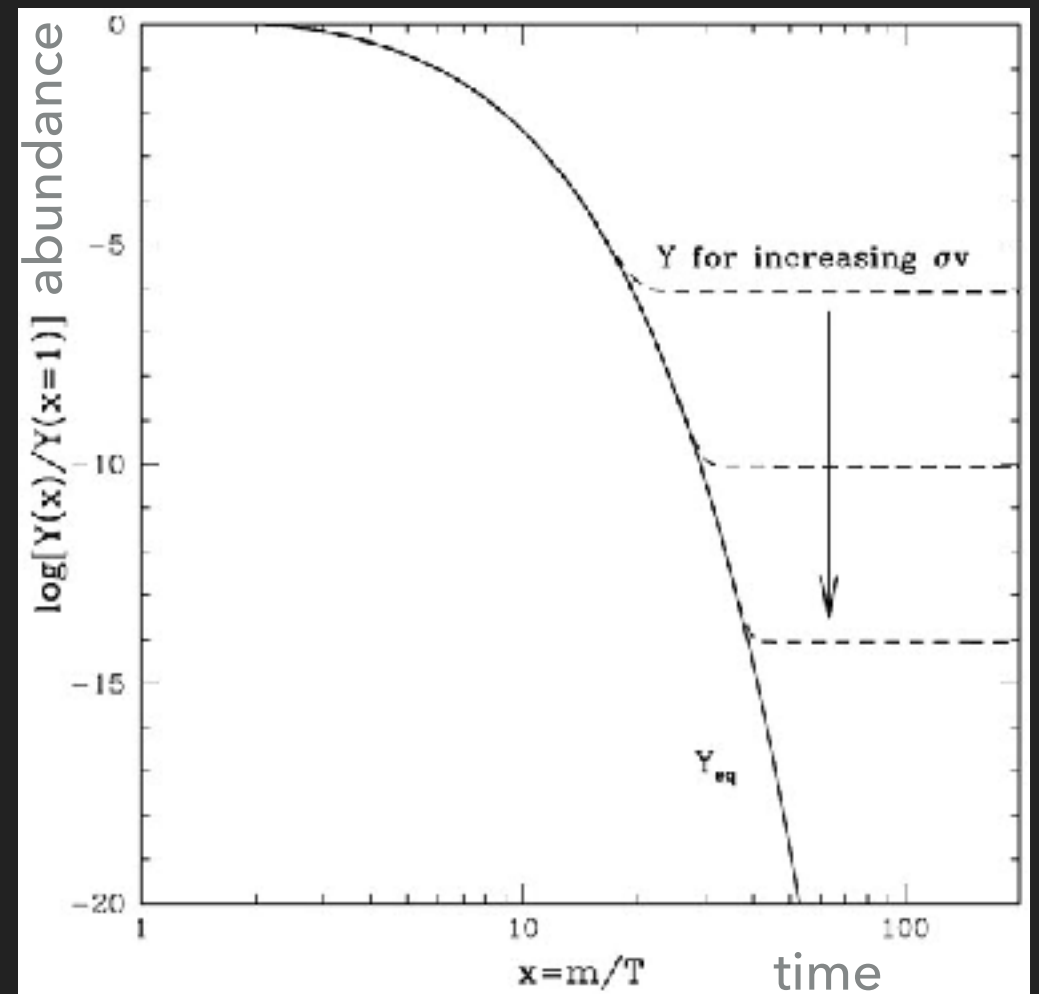
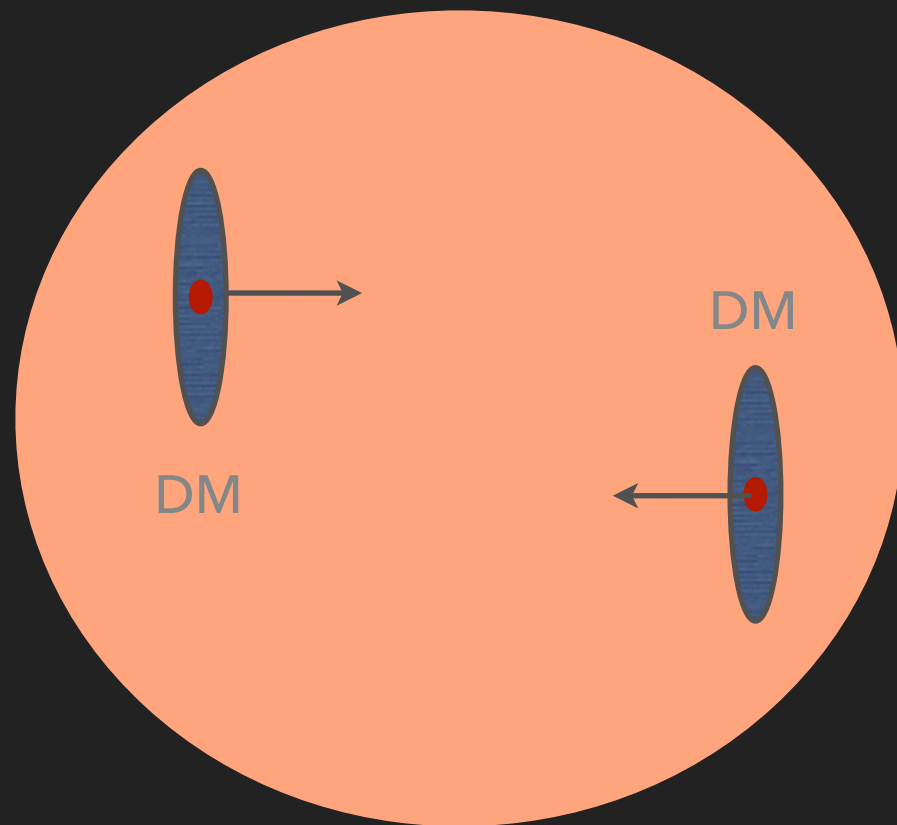
K. ZUREK

Leveraging the many faces (and phases) of matter

BROADENING THE SEARCHLIGHT: NEW IDEAS IN DARK MATTER DETECTION

NEW IDEAS IN DARK MATTER THEORY

- ▶ Old paradigm: weak scale dark matter (with relic density fixed by freeze-out)



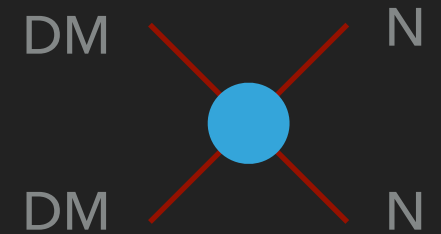
Kolb and Turner

$$n\langle\sigma v\rangle = H(T_{fo})$$

$$\implies \langle\sigma v\rangle \simeq \frac{1}{(20 \text{ TeV})^2} \simeq \frac{g_{wk}^4}{4\pi(2 \text{ TeV})^2}$$

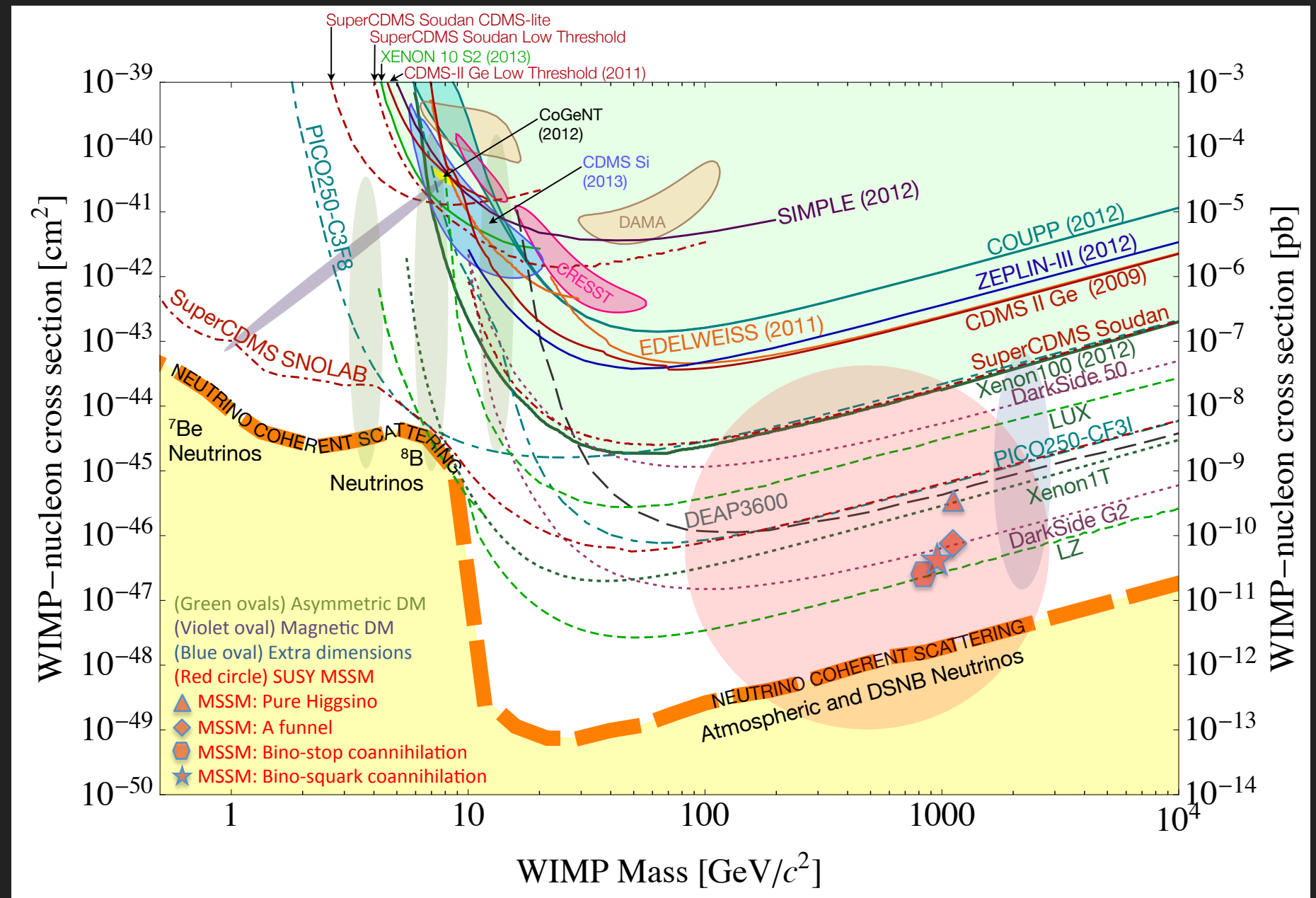
MOTIVATION

WEAK SCALE PARADIGM: UNDER ASSAULT

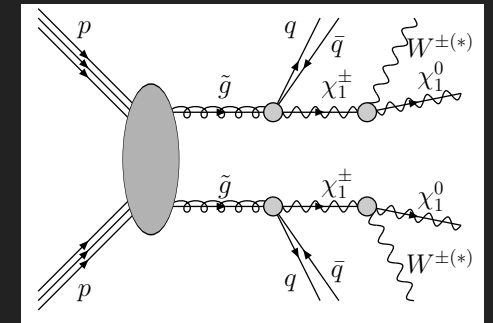


Z-boson interacting
dark matter: ruled out

Higgs interacting dark
matter: active target



WEAK SCALE PARADIGM: UNDER ASSAULT



ATLAS SUSY Searches* - 95% CL Lower Limits

Status: August 2016

Model	e, μ, τ, γ	Jets	L_{int}^{obs} [fb]	Mass limit	$\sqrt{s} = 7, 8, 13$ TeV	$\sqrt{s} = 13, 14$ TeV
Inclusive Searches						
MSUGRA/CMSSM	$0-2 e, \mu, 1-2 \tau$	2-10 jets	Yes	20.3	1.85 TeV	$m(\tilde{g}) \geq m(\tilde{g})$
$\tilde{q}\tilde{q} \rightarrow q\bar{q}$	0	2-6 jets	Yes	13.3	1.33 TeV	$m(\tilde{q}) \geq 200$ GeV, $m(1^{\text{st}} \text{ gen. } \tilde{\chi}) \geq m(2^{\text{nd}} \text{ gen. } \tilde{\chi})$
$\tilde{q}\tilde{q} \rightarrow q\bar{q}$ (compressed)	mono-jet	1-3 jets	Yes	3.2	601 GeV	$m(\tilde{q}) - m(\tilde{\chi}^0) \leq 5$ GeV
$\tilde{g}\tilde{g} \rightarrow g g$	0	2-6 jets	Yes	13.3	1.85 TeV	$m(\tilde{g}) \geq 100$ GeV
$\tilde{g}\tilde{g} \rightarrow g g$	0	2-6 jets	Yes	13.3	1.23 TeV	$m(\tilde{g}) \geq 400$ GeV, $m(\tilde{\chi}^0) \geq 0.5 m(\tilde{g})$
$\tilde{g}\tilde{g} \rightarrow g g$	3 e, μ	4 jets	Yes	13.2	1.7 TeV	$m(\tilde{g}) \geq 400$ GeV
$\tilde{g}\tilde{g} \rightarrow g g$	2 e, μ (SS)	0-3 jets	Yes	13.2	1.6 TeV	$m(\tilde{g}) \geq 500$ GeV
GMSB (NLSP)	1-2 $\tau + 0-1 e$	0-2 jets	Yes	3.2	20 TeV	
GGM (higgs NLSP)	2 τ	-	Yes	2.2	1.65 TeV	$m(\tilde{g}) \geq 100$ GeV
GGM (higgsino NLSP)	γ	1-2 jets	Yes	20.3	1.37 TeV	$m(\tilde{g}) \geq 250$ GeV, $m(\tilde{\chi}^0) \geq 1.1 m(\tilde{g})$
GGM (higgsino NLSP)	γ	2 jets	Yes	13.3	1.3 TeV	$m(\tilde{g}) \geq 450$ GeV, $m(\tilde{\chi}^0) \geq 1.1 m(\tilde{g})$
GGM (higgsino NLSP)	2 e, μ (Z)	2 jets	Yes	20.3	900 GeV	$m(\tilde{g}) \geq 450$ GeV
Gravitino LSP	0	mono-jet	Yes	20.3	891 GeV	$m(\tilde{g}) \geq 10^{-4}$ eV, $m(\tilde{g}) \geq 1$ ETeV
Top pair production						
$\tilde{t}\tilde{t} \rightarrow t\bar{t}$	0	3 b	Yes	14.8	1.39 TeV	$m(\tilde{t}) \geq 0$ GeV
$\tilde{t}\tilde{t} \rightarrow t\bar{t}$	2-1 e, μ	3 b	Yes	14.8	1.39 TeV	$m(\tilde{t}) \geq 0$ GeV
$\tilde{t}\tilde{t} \rightarrow t\bar{t}$	2-1 e, μ	3 b	Yes	20.1	1.37 TeV	$m(\tilde{t}) \geq 200$ GeV
Stop pair production						
$\tilde{s}\tilde{s} \rightarrow s\bar{s}$	0	2 b	Yes	3.2	840 GeV	$m(\tilde{s}) \geq 100$ GeV
$\tilde{s}\tilde{s} \rightarrow s\bar{s}$	2 e, μ (SS)	1 b	Yes	13.2	320-620 GeV	$m(\tilde{s}) \geq 150$ GeV, $m(\tilde{\chi}^0) \geq m(\tilde{s}) - 100$ GeV
$\tilde{s}\tilde{s} \rightarrow s\bar{s}$	2-2 e, μ	1-2 b	Yes	4.7/13.3	17-170 GeV	$m(\tilde{s}) \geq 2m(\tilde{\chi}^0)$, $m(\tilde{\chi}^0) \geq 55$ GeV
$\tilde{s}\tilde{s} \rightarrow s\bar{s}$	2-2 e, μ	1-2 jets/1-2 b	Yes	4.7/13.3	90-194 GeV	$m(\tilde{s}) \geq 100$ GeV
$\tilde{s}\tilde{s} \rightarrow s\bar{s}$	0	mono-jet	Yes	3.2	90-223 GeV	$m(\tilde{s}) \geq m(\tilde{\chi}^0) - 5$ GeV
$\tilde{s}\tilde{s} \rightarrow s\bar{s}$	2 e, μ (Z)	1 b	Yes	20.3	100-600 GeV	$m(\tilde{s}) \geq 150$ GeV
$\tilde{s}\tilde{s} \rightarrow s\bar{s}$	2 e, μ (Z)	1 b	Yes	13.3	250-700 GeV	$m(\tilde{s}) \geq 300$ GeV
$\tilde{s}\tilde{s} \rightarrow s\bar{s}$	1 e, μ	6 jets + 2 b	Yes	20.3	320-620 GeV	$m(\tilde{s}) \geq 0$ GeV
EW pair						
$\tilde{t}\tilde{t} \rightarrow t\bar{t}$	2 e, μ	0	Yes	20.3	30-335 GeV	$m(\tilde{t}) \geq 0$ GeV
$\tilde{t}\tilde{t} \rightarrow t\bar{t}$	2 e, μ	0	Yes	20.3	140-475 GeV	$m(\tilde{t}) \geq 100$ GeV, $m(\tilde{\chi}^0) \geq m(\tilde{t}) - 100$ GeV
$\tilde{t}\tilde{t} \rightarrow t\bar{t}$	2 τ	-	Yes	20.3	255 GeV	$m(\tilde{t}) \geq 100$ GeV, $m(\tilde{\chi}^0) \geq m(\tilde{t}) - 100$ GeV
$\tilde{t}\tilde{t} \rightarrow t\bar{t}$	3 e, μ	0	Yes	20.3	713 GeV	$m(\tilde{t}) \geq 100$ GeV, $m(\tilde{\chi}^0) \geq m(\tilde{t}) - 100$ GeV
$\tilde{t}\tilde{t} \rightarrow t\bar{t}$	2 e, μ	0-2 jets	Yes	20.3	425 GeV	$m(\tilde{t}) \geq 100$ GeV, $m(\tilde{\chi}^0) \geq m(\tilde{t}) - 100$ GeV
$\tilde{t}\tilde{t} \rightarrow t\bar{t}$	4 e, μ	0	Yes	20.3	270 GeV	$m(\tilde{t}) \geq 100$ GeV, $m(\tilde{\chi}^0) \geq m(\tilde{t}) - 100$ GeV
$\tilde{t}\tilde{t} \rightarrow t\bar{t}$	4 e, μ	0	Yes	20.3	635 GeV	$m(\tilde{t}) \geq 100$ GeV, $m(\tilde{\chi}^0) \geq m(\tilde{t}) - 100$ GeV
GGM (higgs NLSP) weak prod.	1 e, μ + γ	-	Yes	20.3	112-370 GeV	$m(\tilde{g}) \geq 100$ GeV
GGM (higgs NLSP) weak prod.	2 τ	-	Yes	20.3	255 GeV	$m(\tilde{g}) \geq 100$ GeV
Long lived						
Direct $\tilde{t}\tilde{t}$ prod., long-lived \tilde{t}	Disapp. trk	1 jet	Yes	20.3	270 GeV	$m(\tilde{t}) \geq m(\tilde{\chi}^0) - 80$ MeV, $m(\tilde{t}) \geq 1.2$ TeV
Direct $\tilde{t}\tilde{t}$ prod., long-lived \tilde{t}	disapp. trk	-	Yes	18.4	495 GeV	$m(\tilde{t}) \geq m(\tilde{\chi}^0) - 80$ MeV, $m(\tilde{t}) \geq 1.5$ TeV
Stable stopped \tilde{t} R-hadron	0	1-5 jets	Yes	27.9	850 GeV	$m(\tilde{t}) \geq 100$ GeV, $m(\tilde{\chi}^0) \geq 1000$ GeV
Stable \tilde{t} R-hadron	trk	-	-	3.2	1.85 TeV	
Metastable \tilde{t} R-hadron	disapp. trk	-	-	3.2	1.57 TeV	$m(\tilde{t}) \geq 100$ GeV, $m(\tilde{\chi}^0) \geq 1000$ GeV
GMSB, stable \tilde{t} $\tilde{t} \rightarrow t\bar{t} + \tilde{\chi}^0$	1-2 μ	-	-	19.1	330 GeV	$m(\tilde{t}) \geq 100$ GeV, $m(\tilde{\chi}^0) \geq 1000$ GeV
GMSB, $\tilde{t} \rightarrow t\bar{t} + \tilde{\chi}^0$, long-lived \tilde{t}	2 τ	-	Yes	20.3	440 GeV	$m(\tilde{t}) \geq 100$ GeV, $m(\tilde{\chi}^0) \geq 1000$ GeV
$\tilde{g}\tilde{g} \rightarrow g g$	displ. $ee \rightarrow \mu\mu$	-	-	20.3	1.3 TeV	$m(\tilde{g}) \geq 100$ GeV, $m(\tilde{\chi}^0) \geq 1000$ GeV
GGM $\tilde{g}\tilde{g} \rightarrow g g$	displ. $ee \rightarrow \mu\mu$	-	-	20.3	1.3 TeV	$m(\tilde{g}) \geq 100$ GeV, $m(\tilde{\chi}^0) \geq 1000$ GeV
RPV						
LFV $\tilde{g}\tilde{g} \rightarrow g g$	disapp. trk	-	-	3.2	1.8 TeV	$m(\tilde{g}) \geq 100$ GeV, $m(\tilde{\chi}^0) \geq 1000$ GeV
Bilinear RPV CMSSM	2 e, μ (SS)	0-2 jets	Yes	20.3	1.45 TeV	$m(\tilde{g}) \geq 100$ GeV, $m(\tilde{\chi}^0) \geq 1000$ GeV
$\tilde{t}\tilde{t} \rightarrow t\bar{t}$	4 e, μ	-	Yes	13.3	1.14 TeV	$m(\tilde{t}) \geq 400$ GeV, $m(\tilde{\chi}^0) \geq 1000$ GeV
$\tilde{t}\tilde{t} \rightarrow t\bar{t}$	2 e, μ + γ	-	Yes	20.3	450 GeV	$m(\tilde{t}) \geq 400$ GeV, $m(\tilde{\chi}^0) \geq 1000$ GeV
$\tilde{t}\tilde{t} \rightarrow t\bar{t}$	0	4-5 large- p_T jets	-	14.8	1.18 TeV	$m(\tilde{t}) \geq 400$ GeV, $m(\tilde{\chi}^0) \geq 1000$ GeV
$\tilde{t}\tilde{t} \rightarrow t\bar{t}$	0	4-5 large- p_T jets	-	14.8	1.35 TeV	$m(\tilde{t}) \geq 400$ GeV, $m(\tilde{\chi}^0) \geq 1000$ GeV
$\tilde{t}\tilde{t} \rightarrow t\bar{t}$	2 e, μ (SS)	0-2 jets	Yes	13.2	1.3 TeV	$m(\tilde{t}) \geq 400$ GeV, $m(\tilde{\chi}^0) \geq 1000$ GeV
$\tilde{t}\tilde{t} \rightarrow t\bar{t}$	0	2 jets + 2 b	-	15.4	410 GeV	$m(\tilde{t}) \geq 400$ GeV, $m(\tilde{\chi}^0) \geq 1000$ GeV
$\tilde{t}\tilde{t} \rightarrow t\bar{t}$	2 e, μ	2 b	-	20.3	0.4-1.3 TeV	$m(\tilde{t}) \geq 400$ GeV, $m(\tilde{\chi}^0) \geq 1000$ GeV
Other						
Search for $\tilde{t} \rightarrow t\bar{t}$	0	2 jets	Yes	20.3	510 GeV	$m(\tilde{t}) \geq 200$ GeV

*Only a selection of the available mass limits on new states or phenomena is shown.

10⁻¹

1

Mass scale [TeV]

TOWARDS LIGHT DARK MATTER

Dark Matter May Reside in a Hidden Sector

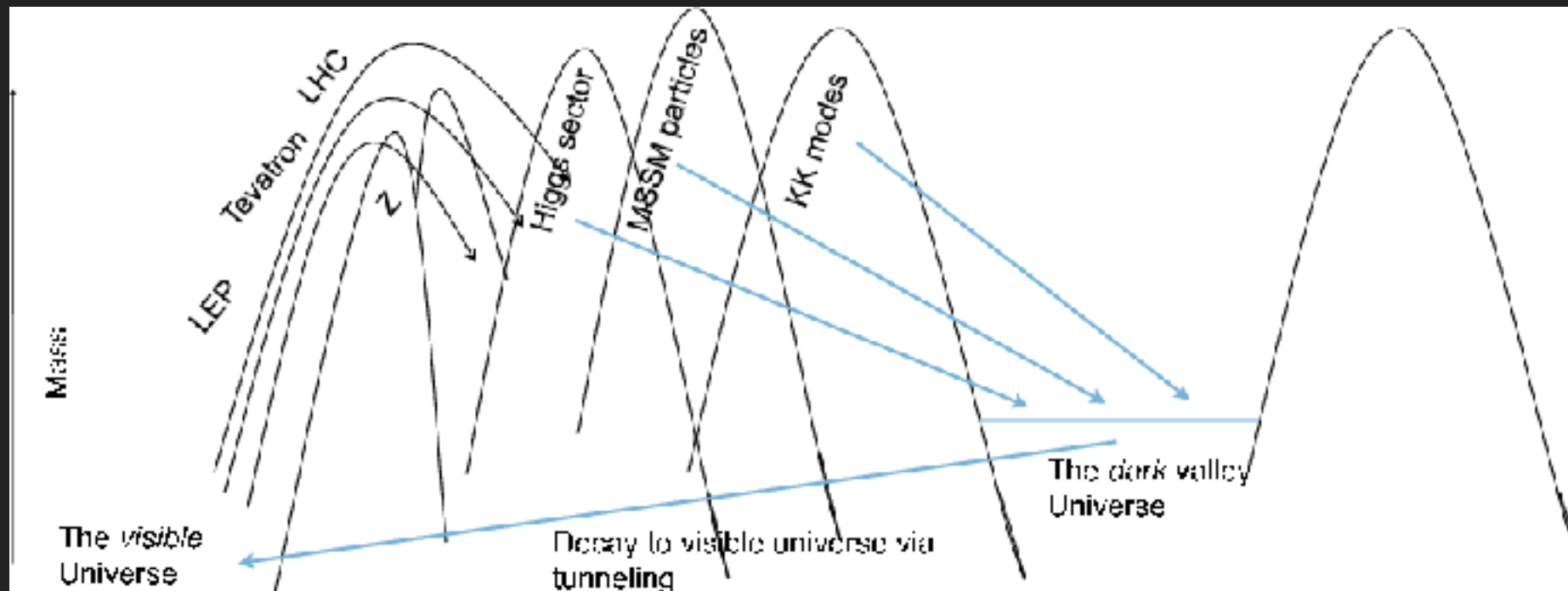
Standard Model



Connector



Dark Matter



e.g. a stable dark pion

no weak force

$$\pi_v^+ \pi_v^- \rightarrow \pi_v^0 \pi_v^0$$

$$\pi_v^0 \rightarrow b\bar{b}, \gamma\gamma$$

Hidden Valley paradigm, Strassler, KZ 2006

BROAD RANGE OF MODELS



Supersymmetric

Hooper, KZ 2008, Feng and Kumar 2008

Arkani-Hamed, Weiner 2008

Baumgart, Cheung et al 2009 ...

Baryogenesis

Buckley & Randall 2010, Cheung & KZ 2011

Fileviez-Perez & Wise 2010, 2013 ...

Non-Abelian

Kribs, Roy, Terning, KZ 2009 ...

Hidden Charged

Pospelov & Ritz 2007, Feng et al 2009 ...

Dark Disk

Fan, Katz, Randall, Reece 2013 ...

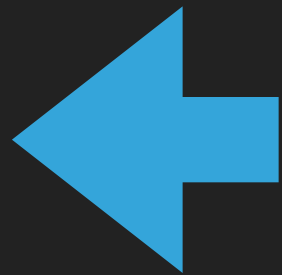
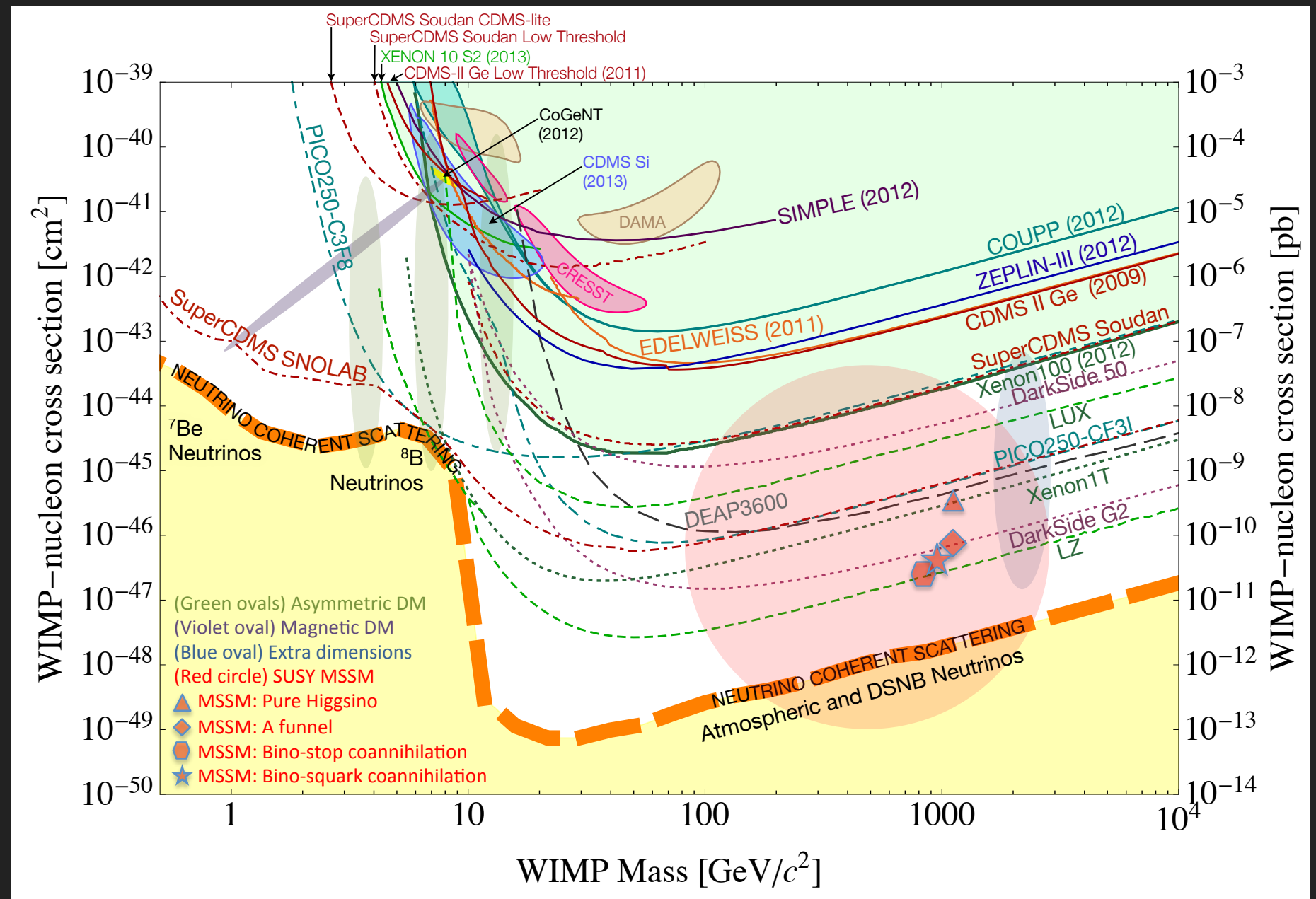
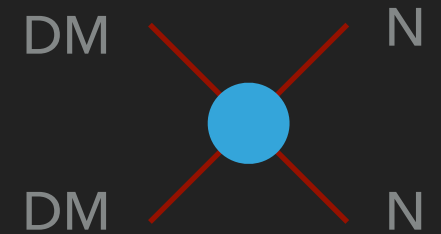
Atomic Kaplan et al 2009 ...

Nuggets

Wise, Zhang 2014 ...

MOTIVATION

WEAK SCALE PARADIGM: UNDER ASSAULT



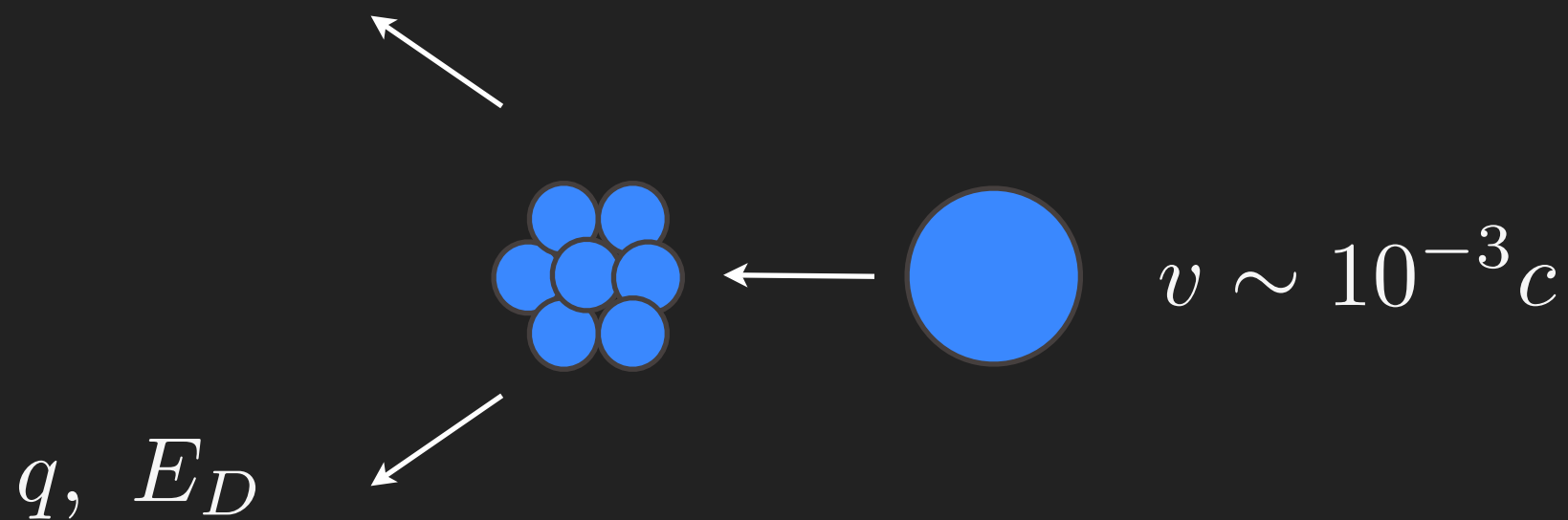
???

BROADENING THE SEARCHLIGHT

- ▶ New detection techniques to search for light dark matter
 - ▶ Sensitive to fainter whispers
 1. "Designer" materials
 2. Super-sensitive calorimeters with low dark counts
- ▶ New modes to detect dark matter
 - ▶ Looking beyond billiard ball nuclear recoils

DIRECT DETECTION GOLD STANDARD

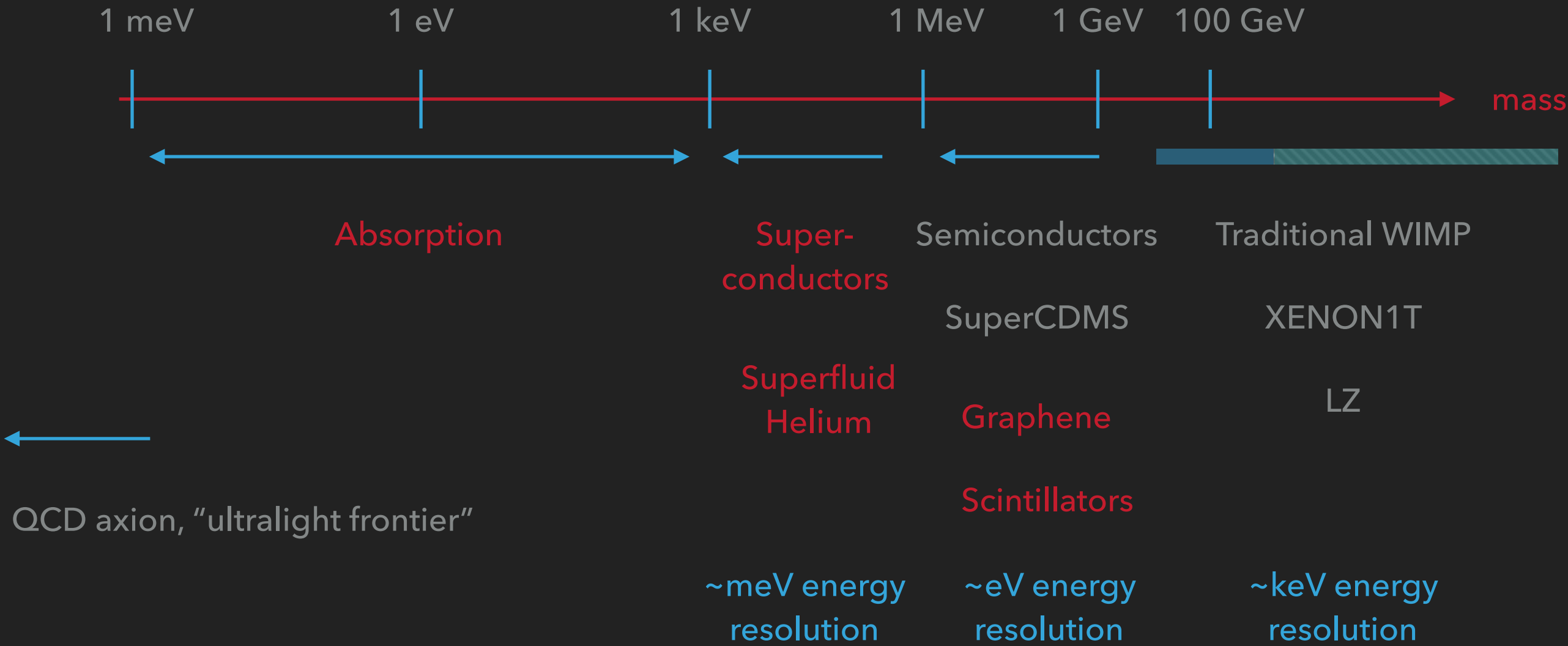
- Nuclear recoil experiments; basis of enormous progress in direct detection



$$\implies 2\mu_N v = q_{\max} = \sqrt{2m_N E_D} \quad \mu_N \equiv \frac{m_N m_X}{m_X + m_N}$$

$$v \sim 300 \text{ km/s} \sim 10^{-3}c \implies E_D \sim 100 \text{ keV} \quad \text{for 50 GeV target}$$

DARK MATTER LANDSCAPE



NUCLEAR RECOILS

- Kinematic penalty when DM mass drops below nucleus mass

$$E_D = \frac{q^2}{2m_N} \quad q_{\max} = 2m_X v$$



$$E_D \gtrsim \text{eV} \Leftrightarrow m_X = 300 \text{ MeV}$$

even though $E_{\text{kin}} \gtrsim 300 \text{ eV}$

COLLECTING HEAT

- ▶ Basic hurdle for detecting light DM:

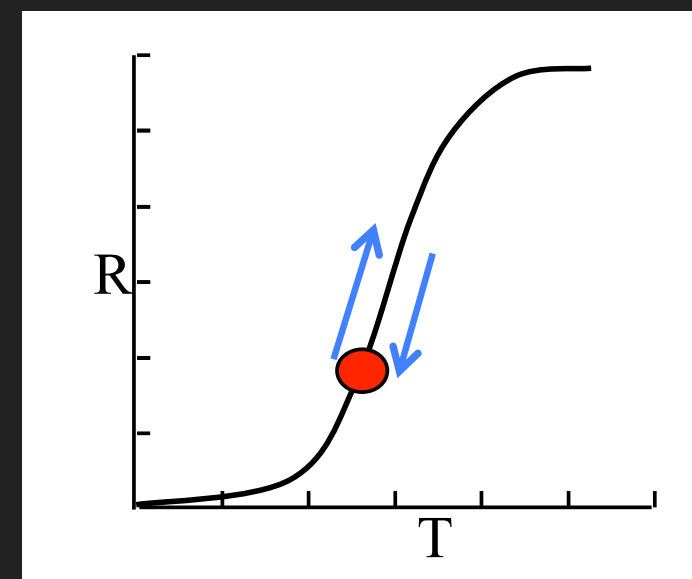
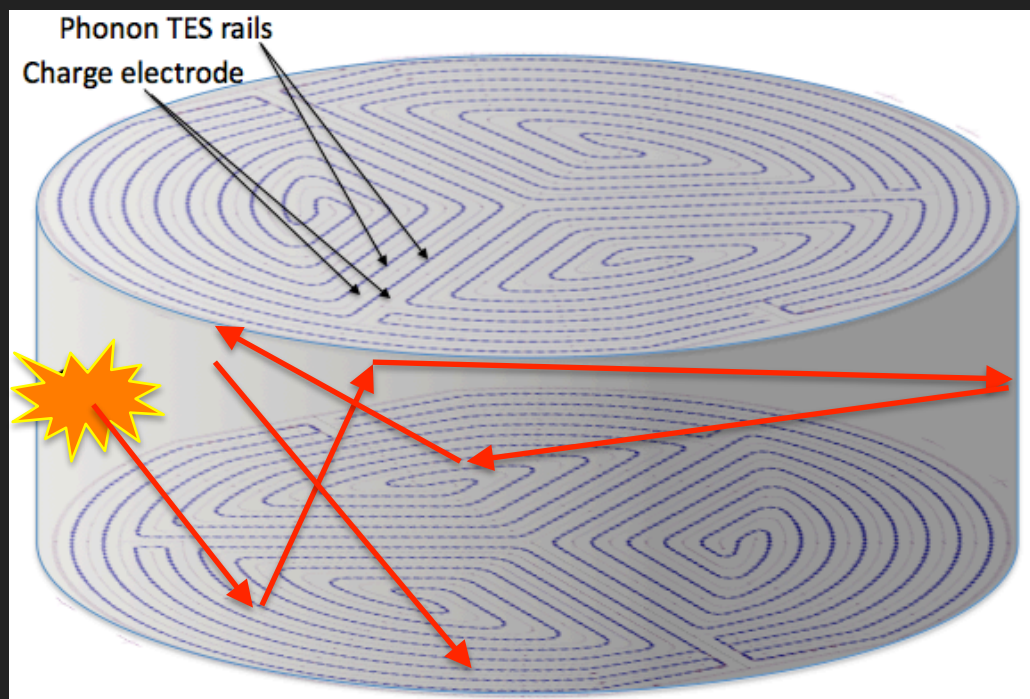
Rare events with little energy deposit!

- ▶ Challenge: creating low enough noise environments to detect whispers
- ▶ Fundamentally limited by the gap
 - ▶ In atoms, ionization energy is at least 10 eV
 - ▶ In semiconductors, band gap is typically > 1 eV

COLLECTING HEAT

- ▶ Principles already in play in current direct detection experiments such as SuperCDMS
- ▶ Large target; concentrate small energy deposits onto small calorimeters

Transition Edge Sensor calorimeter



NEXT UP: ELECTRON

- ▶ More bang for the buck if DM lighter than 1 GeV

$$E_D = \frac{q^2}{2m_e} \qquad q_{\max} = 2m_X v$$

- ▶ Allows to extract all of DM kinetic energy for DM MeV and heavier

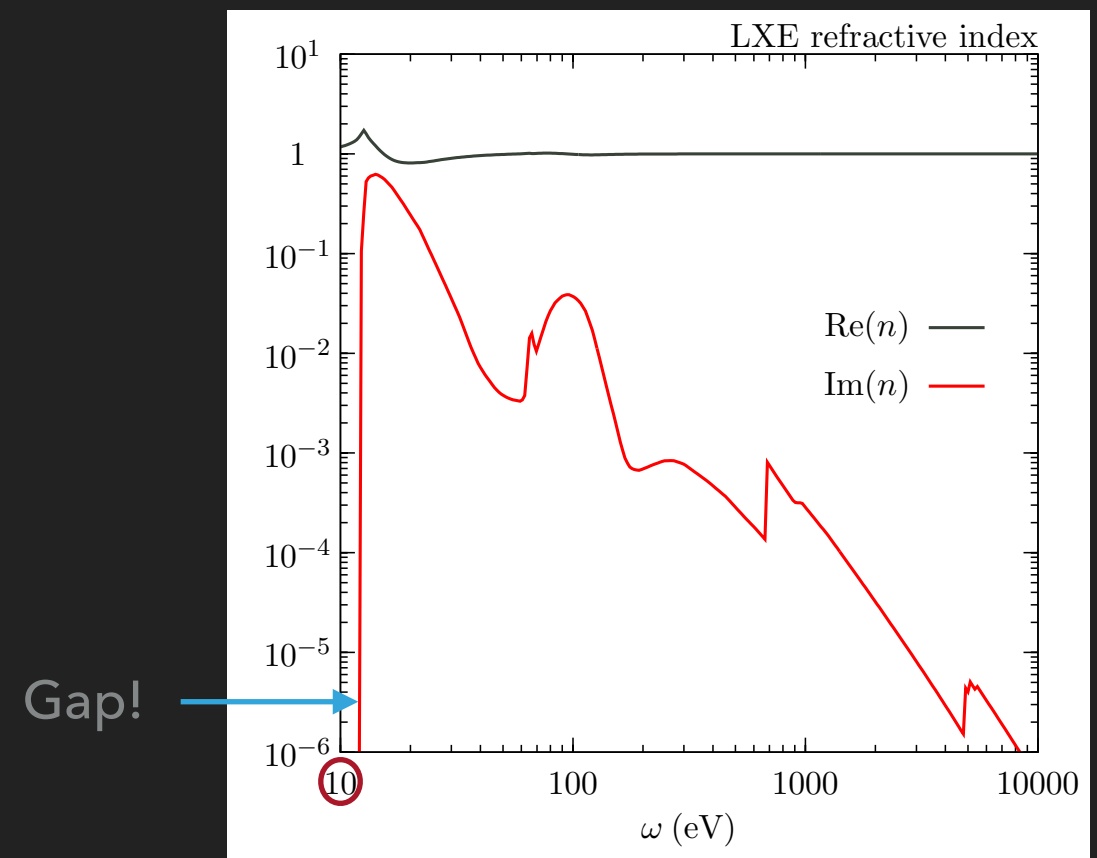
$$E_D \gtrsim \text{eV} \leftrightarrow m_X = 1 \text{ MeV}$$

ELECTRONS IN MATERIALS

- In insulators, like xenon

Tightly bound; ionize for signal

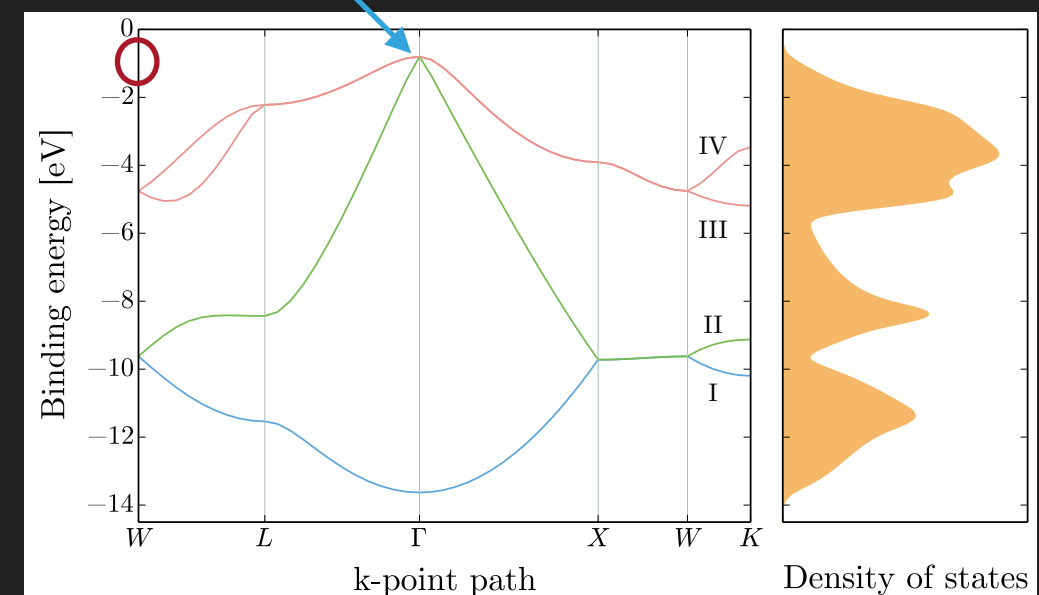
An, Pospelov, Pradler, Ritz 1412.8378



- In semi-conductors, like Ge, Si

Valence electrons become conducting;
presence of collective modes

Lee, Lisanti, Safdi 1508.07361

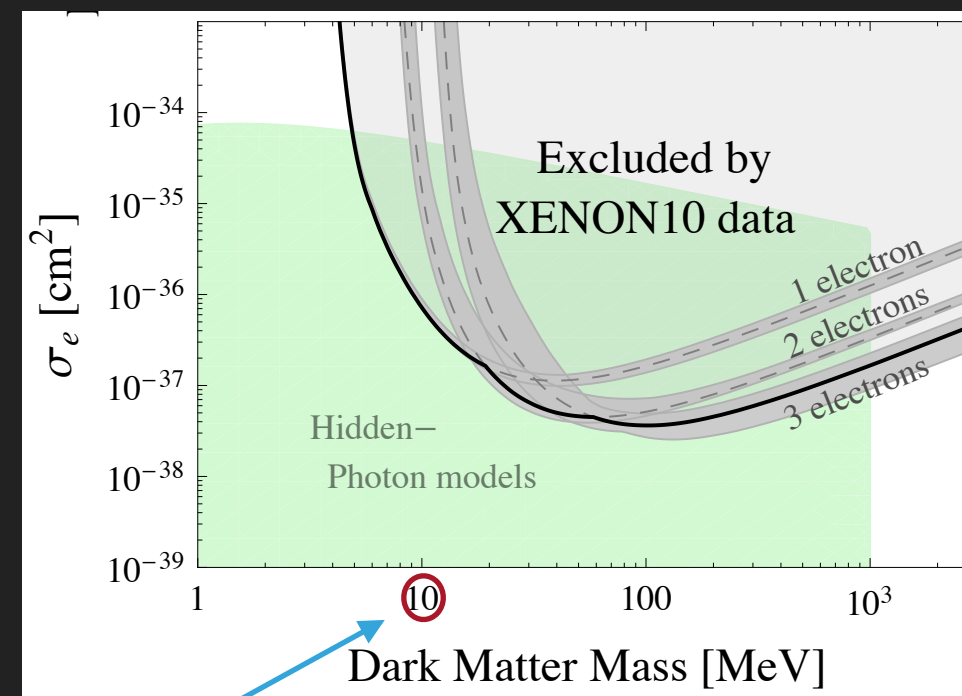


ELECTRONS IN MATERIALS

- ▶ In insulators, like xenon

Tightly bound; ionize for signal

P. Sorensen et al 1206.2644

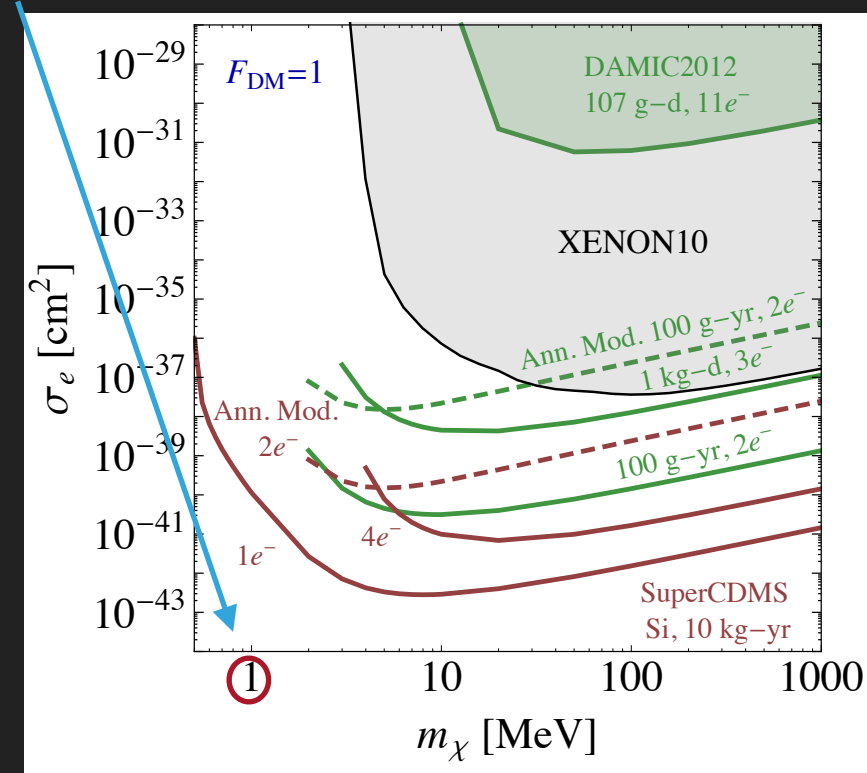


Gap = DM Kinetic Energy

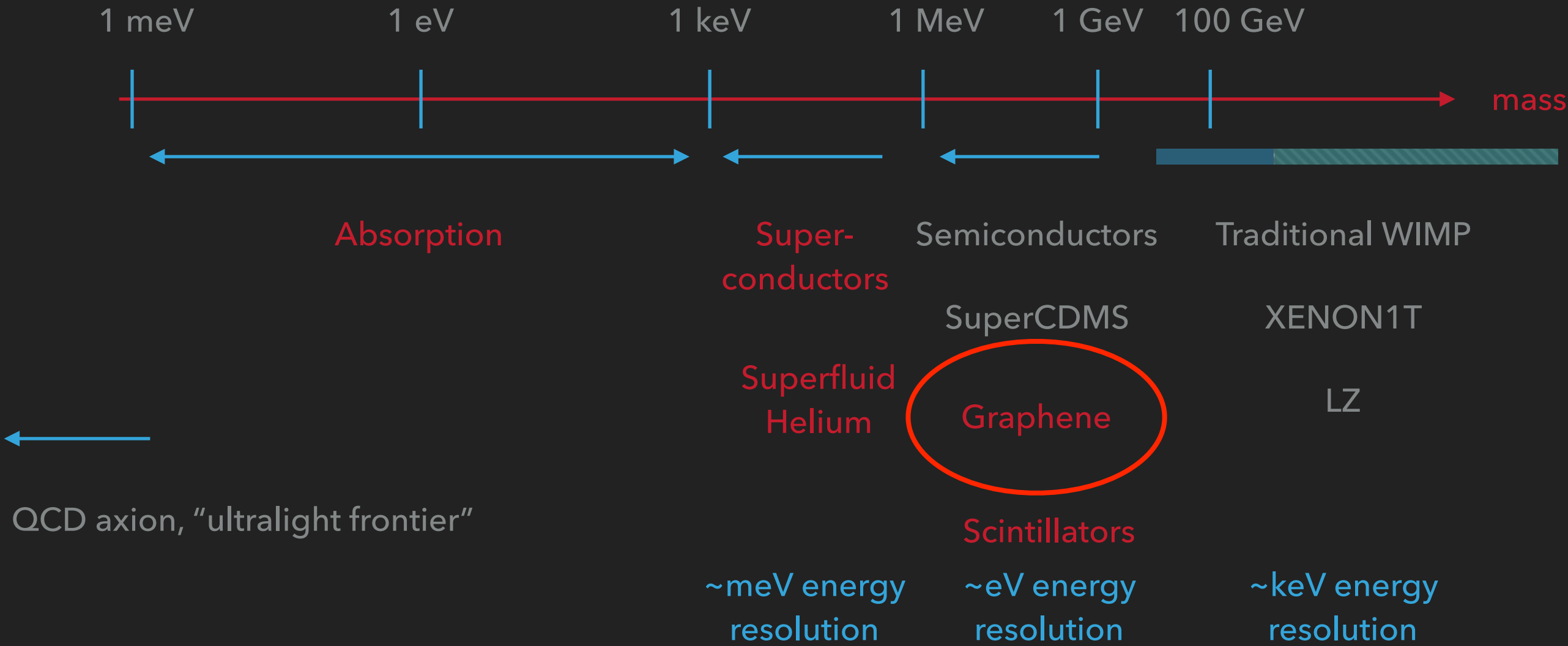
- ▶ In semi-conductors, like Ge, Si

Valence electrons become conducting;
presence of collective modes

Essig et al 1509.01598

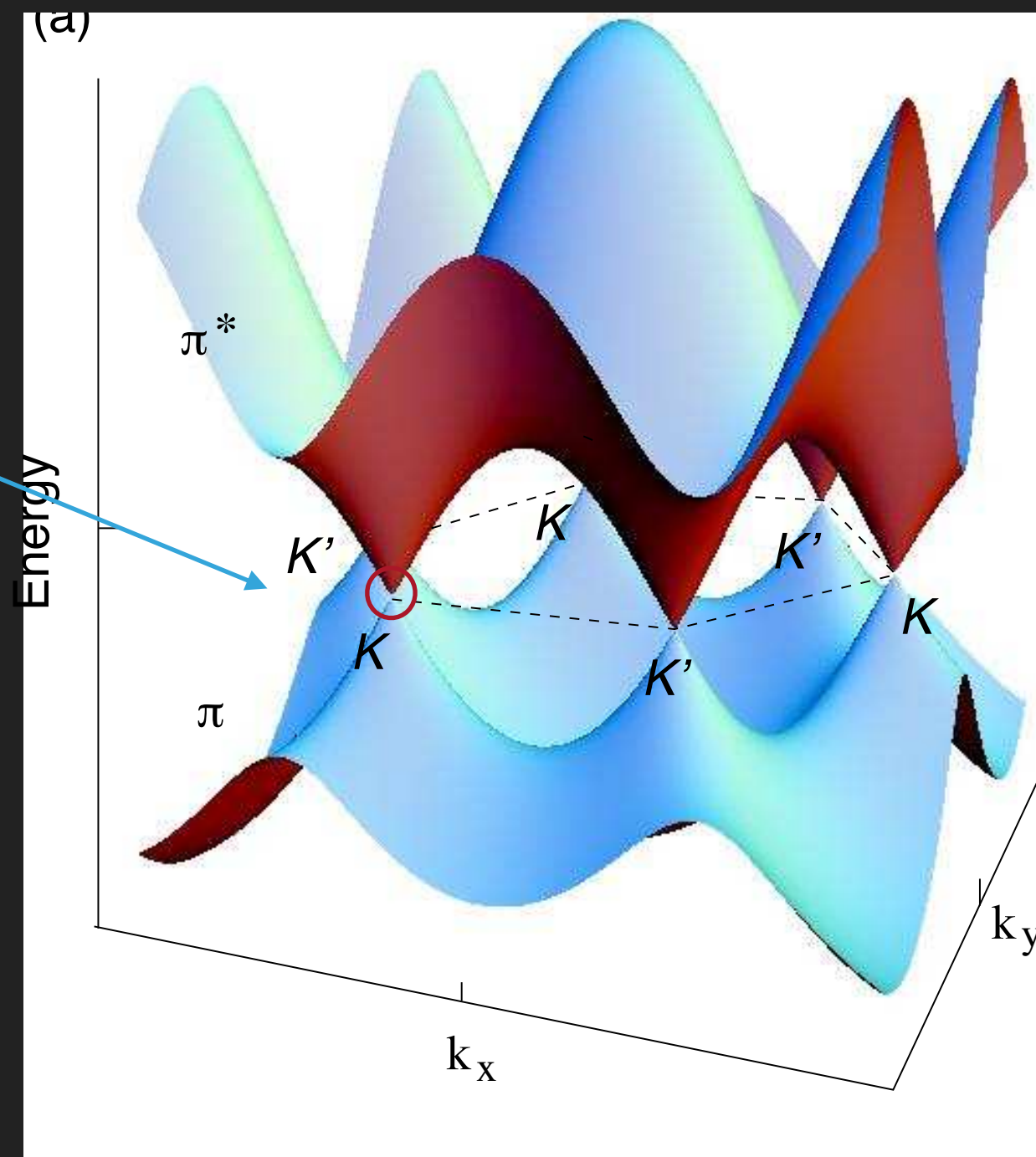
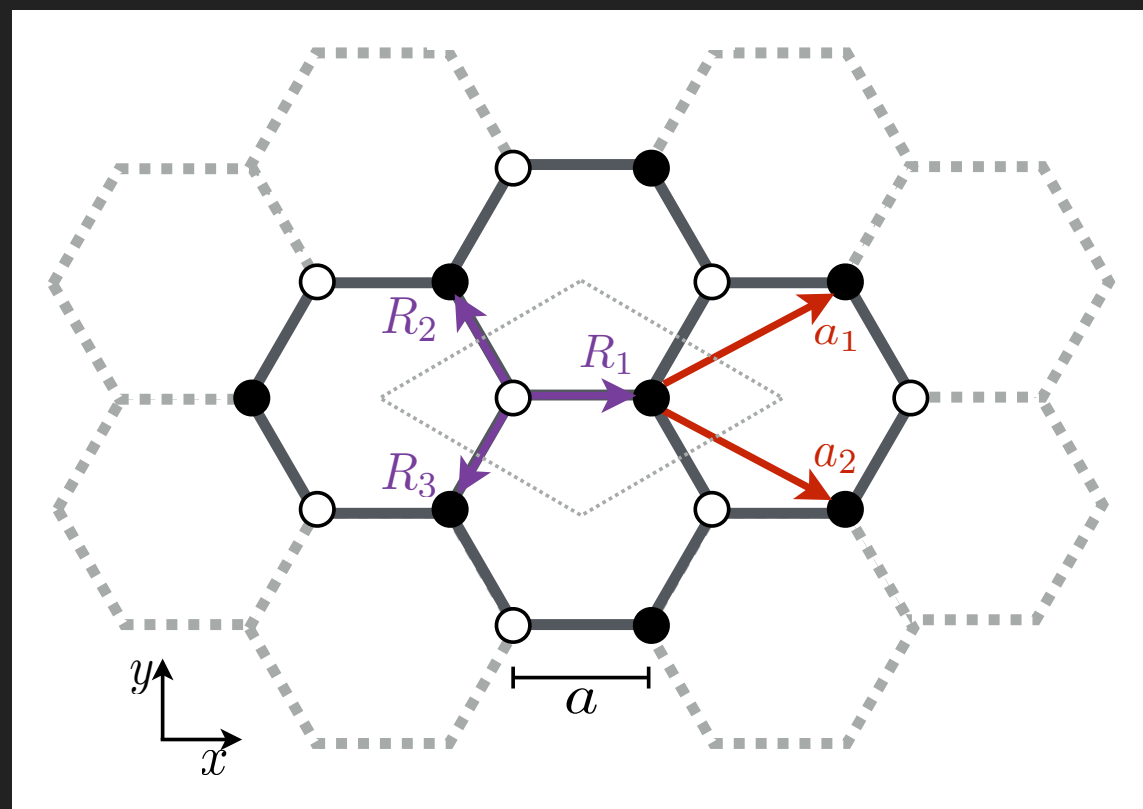


DARK MATTER LANDSCAPE

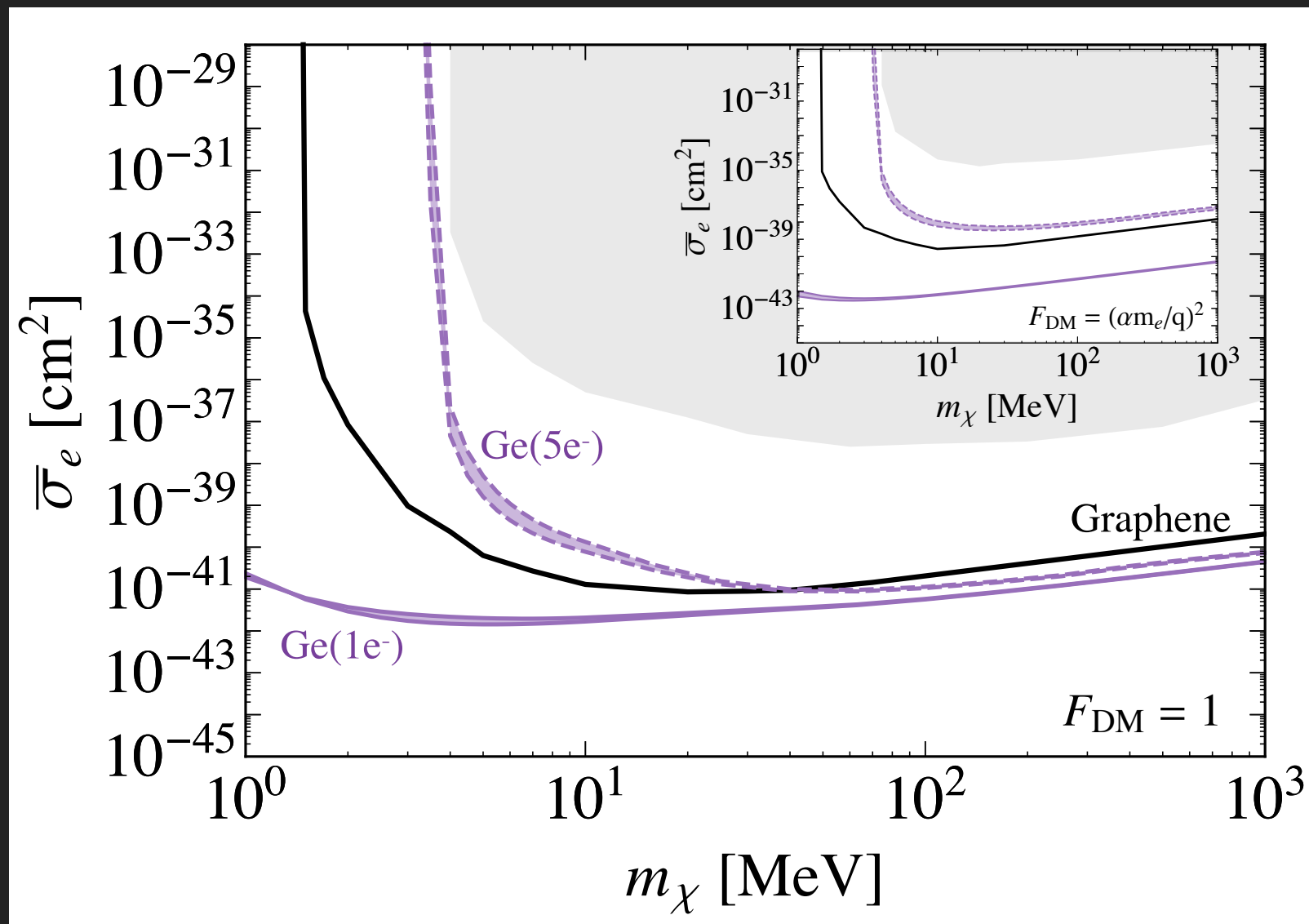


OTHER SMALL GAP MATERIALS — GRAPHENE

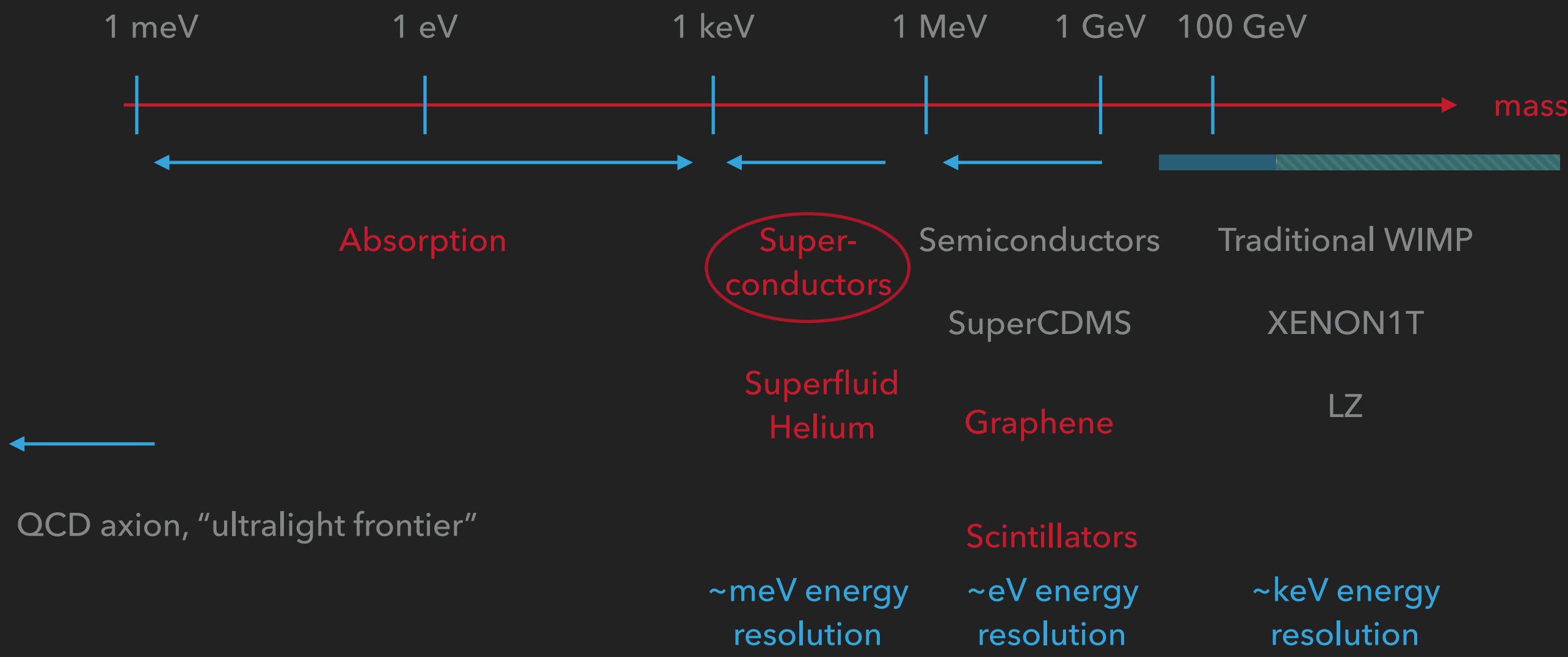
Symmetry structure of material
gives rise to special points with
no gap



DARK MATTER RATE

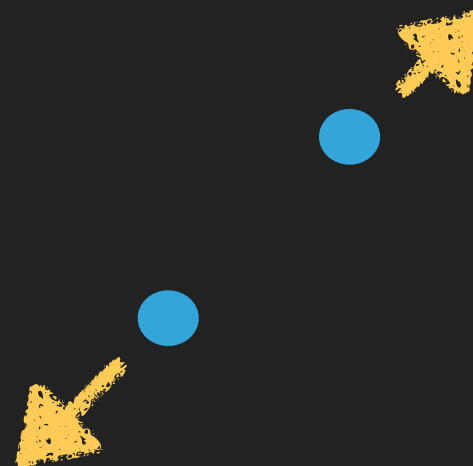
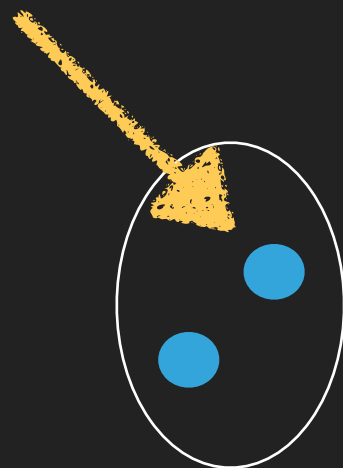
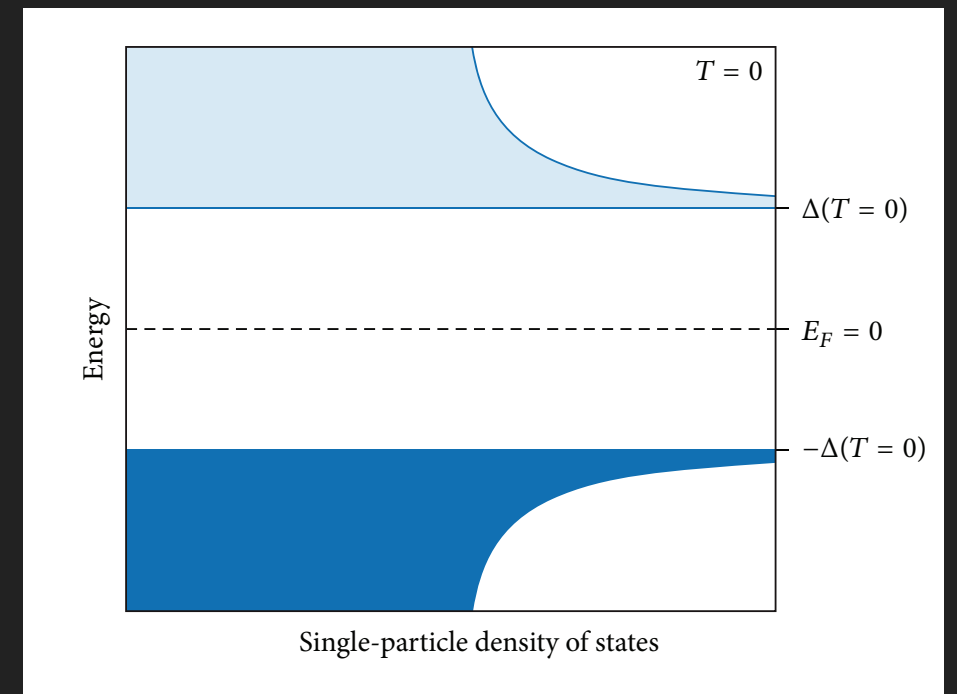


DARK MATTER LANDSCAPE

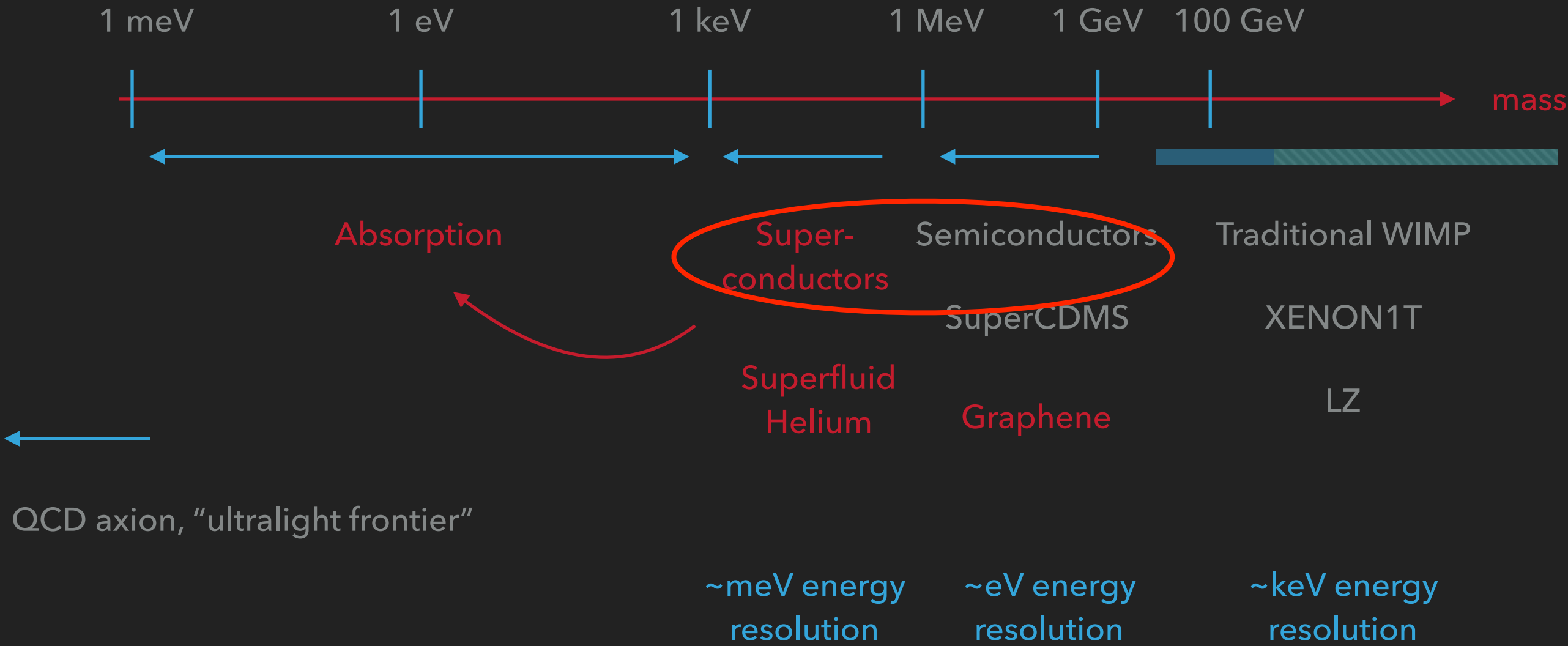


COOPER PAIRS

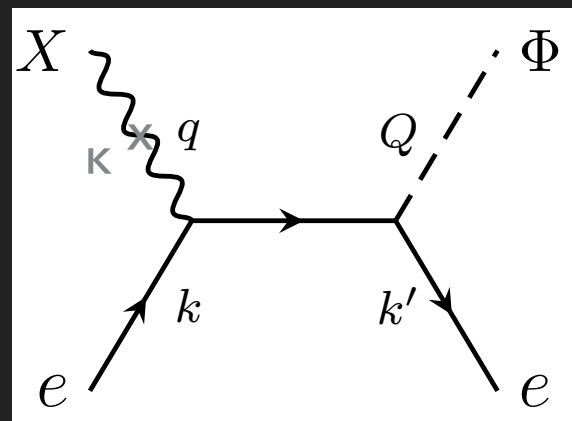
- ▶ Smaller gap $\Delta \simeq 0.3 \text{ meV}$
 - ▶ = more sensitivity to environmental noise
 - ▶ = more sensitivity to light dark matter



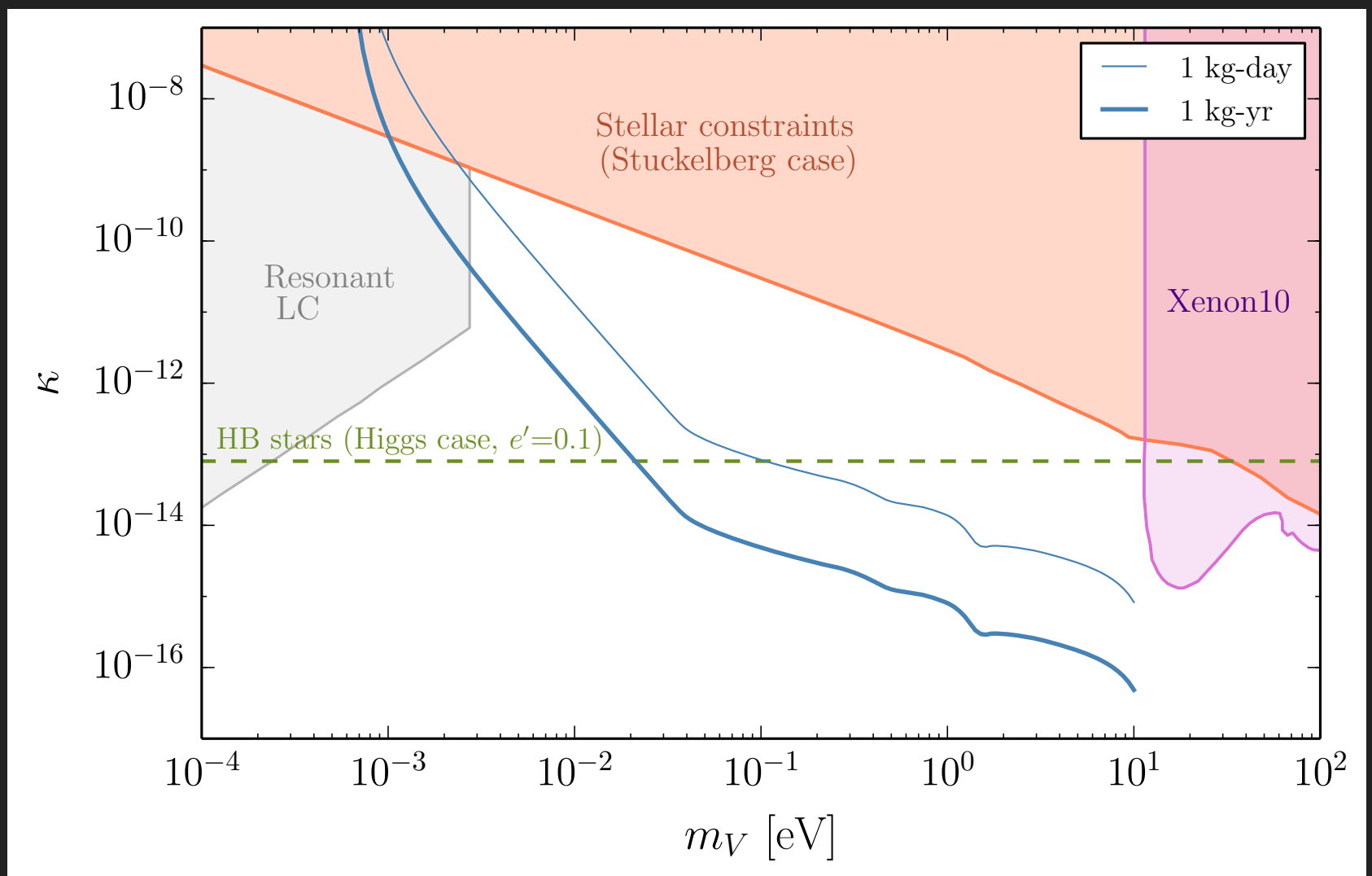
DARK MATTER LANDSCAPE



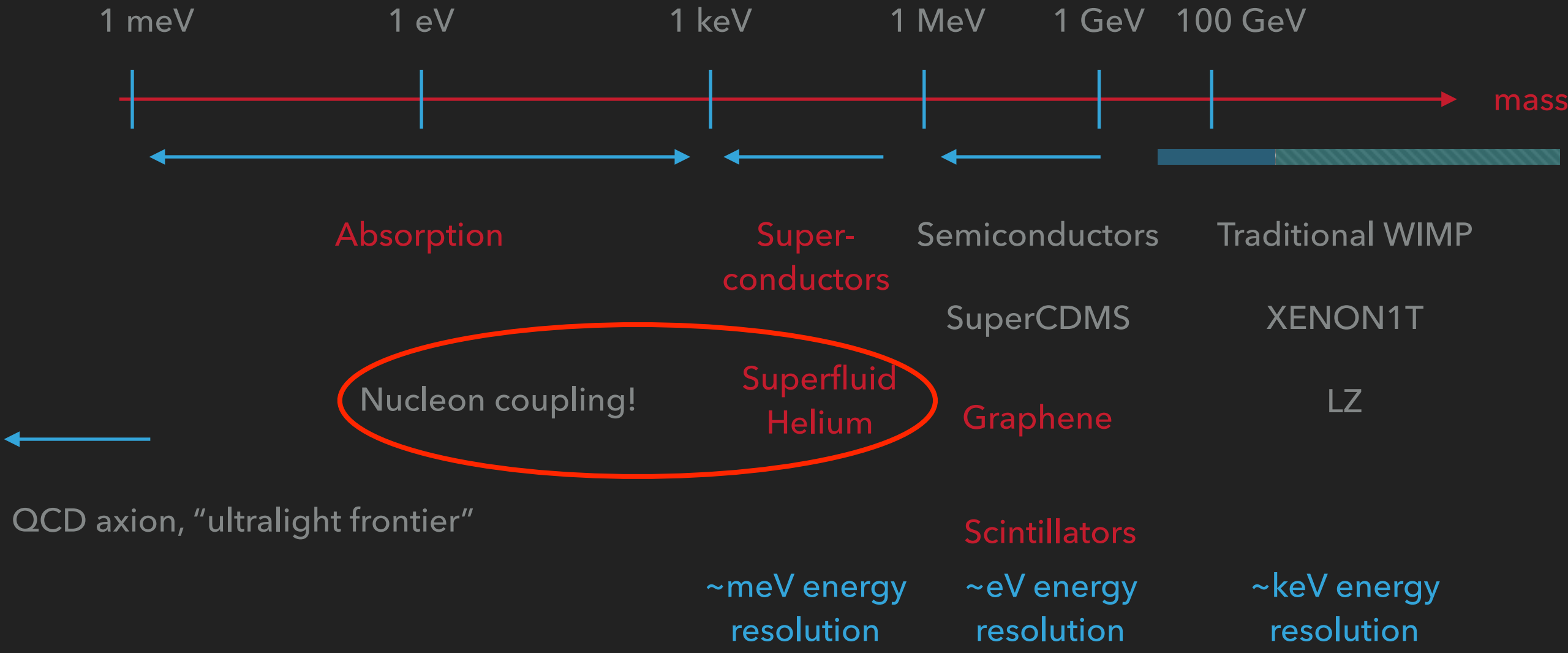
ABSORPTION



Dark Photon



DARK MATTER LANDSCAPE



LOW GAP MATERIAL

- ▶ Superfluids are naturally insensitive to noise. A good light DM detector? In the context of ordinary nuclear recoils, yes, see e.g. McKinsey's group 1605.00694 See talks this session

- ▶ To detect lighter DM, couple to phonon modes.

- ▶ Viable? At first glance – no

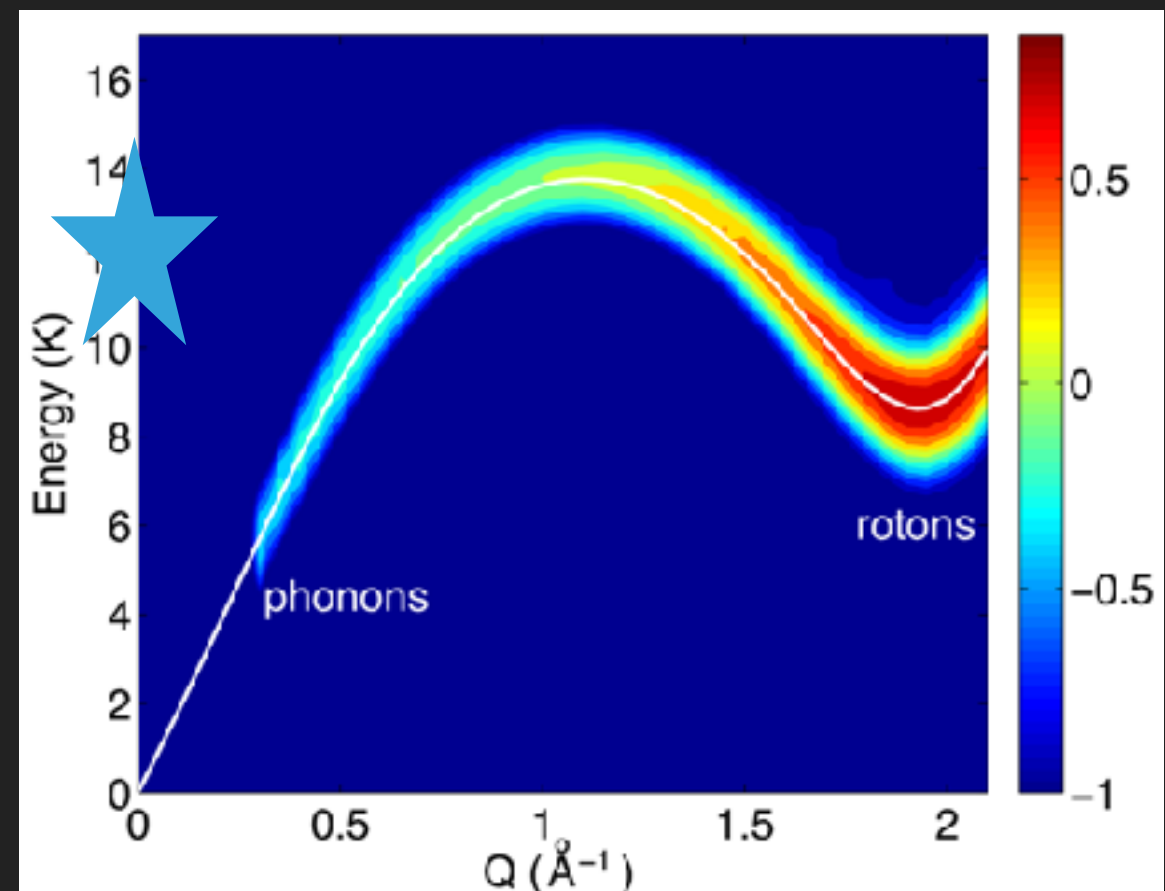
$$E_D \sim v_X q$$

vs

$$c_s \ll v_X$$

$$E_D \sim c_s q$$

- ▶ Next glance -- yes!



LOW GAP MATERIAL

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$$E_D \sim v_X q$$

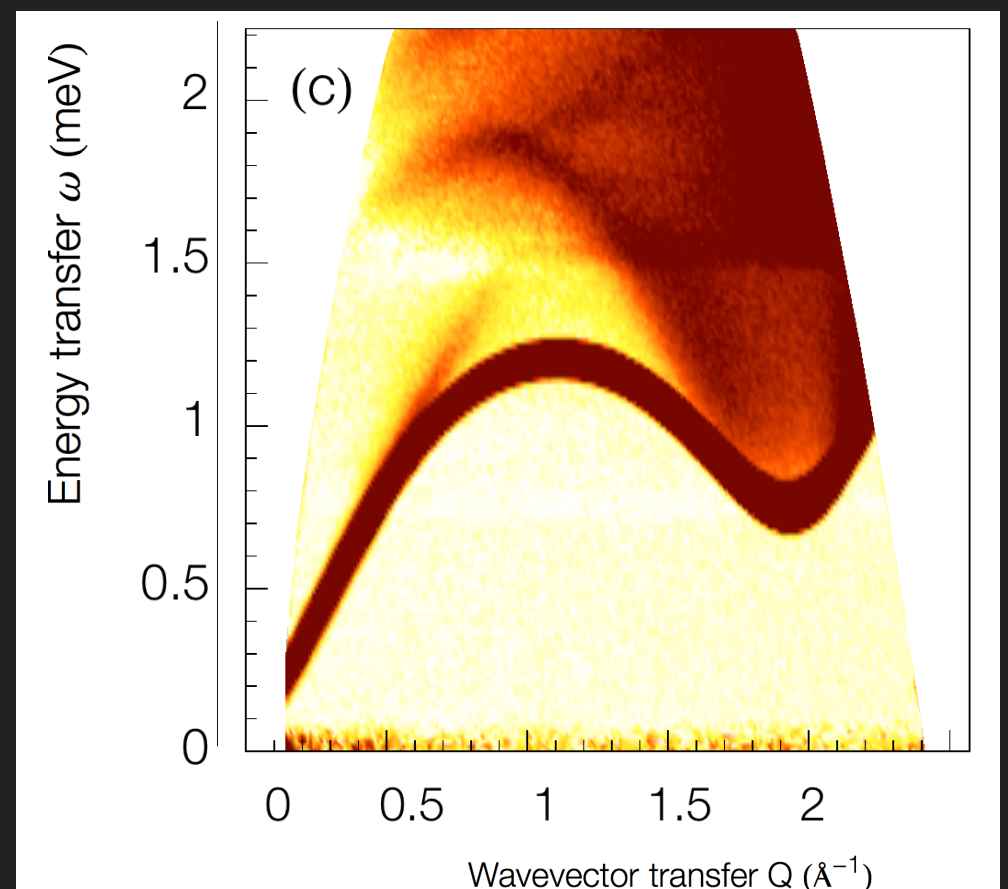
vs

$$c_s \ll v_X$$

$$E_D \sim c_s q$$

- ▶ Next glance -- yes!

Beauvois et al 1605.02638



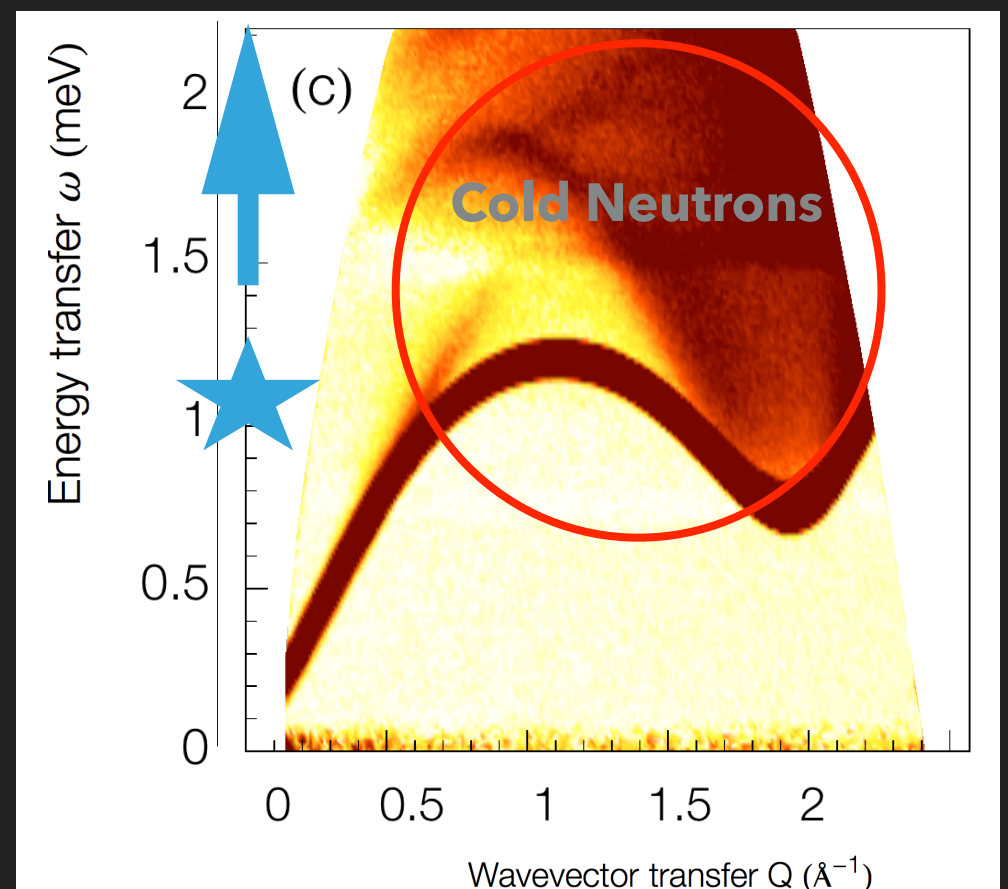
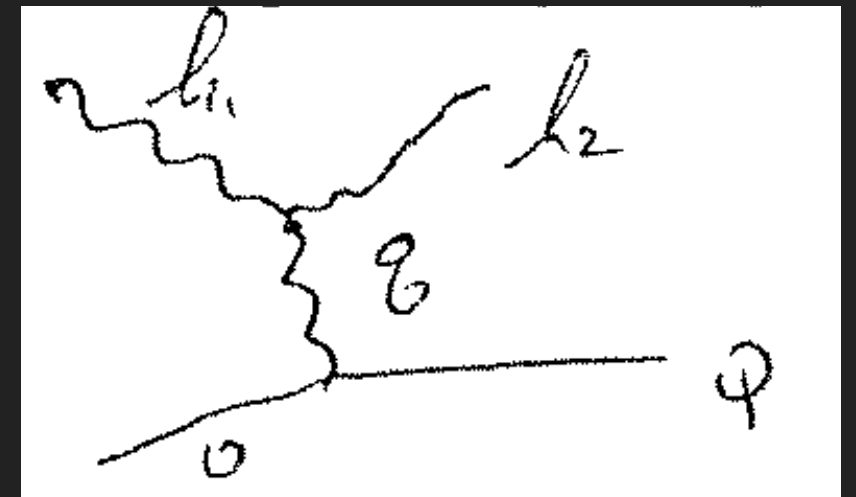
MULTI-EXCITATIONS

- ▶ Calculated and observed for cold neutrons See talk by E. Krotschek

$$V_3 = \int d^3r \left[\frac{\vec{v} \cdot \vec{g}' \vec{u}_4}{2} - \frac{1}{3!} \frac{d}{d\vec{g}} \left(\frac{c^2}{\vec{g}} \right) (\vec{g}')^3 \right]$$

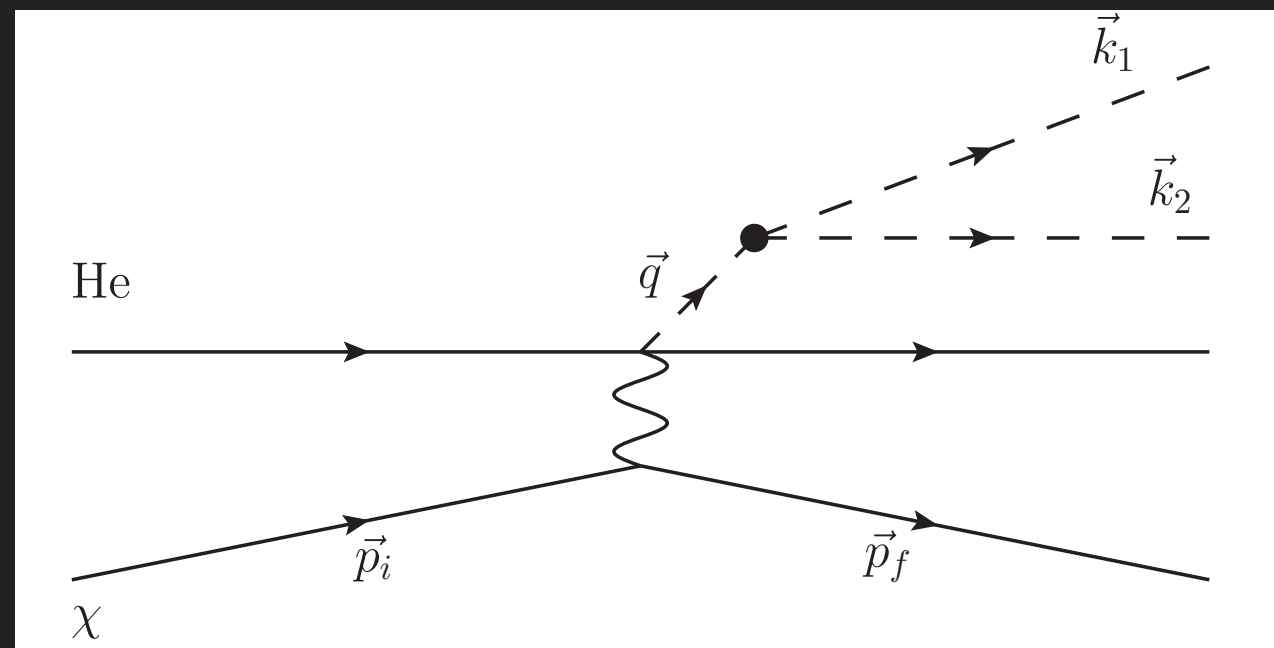
- ▶ However, this is in a very different kinematic regime
- ▶ No existing calculations in regime of interest

Internal note, R. Golub, 1977



MULTI-EXCITATIONS

- ▶ emit back-to-back excitations to bleed off energy while conserving momentum



HOW TO CALCULATE?

- ▶ Theory developed by Landau-Khalatnikov and Feynman-Cohen
- ▶ Quantize the fluid Hamiltonian, like SHO

$$H_0 = \frac{1}{2} \sum_k \left(\rho_0 v_{\vec{k}} v_{-\vec{k}} + \phi(k) \rho_{\vec{k}} \rho_{-\vec{k}} \right) \quad m_{\text{He}}^2 S(k) = \langle \rho_k \rho_{-k} \rangle$$

- ▶ Fluid is strongly coupled; excitations are propagating in interacting background (requires care)

RATE

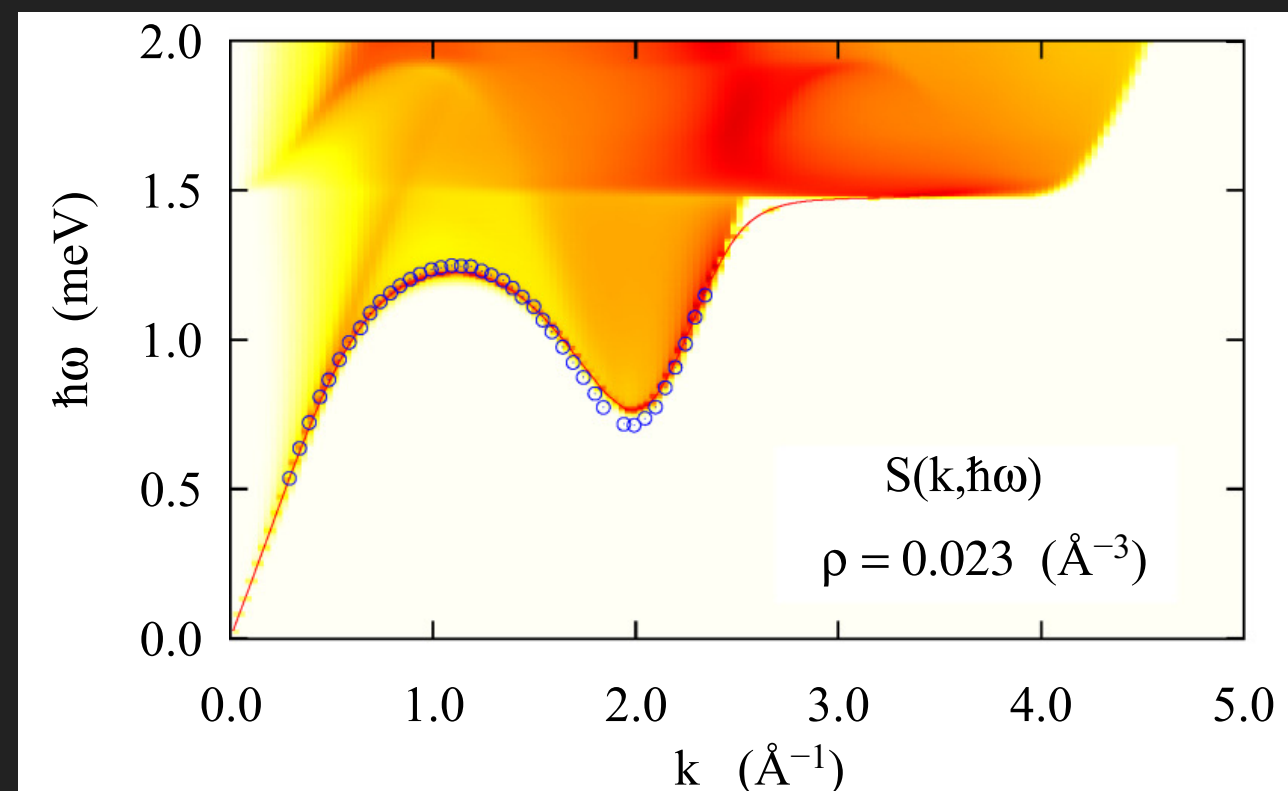
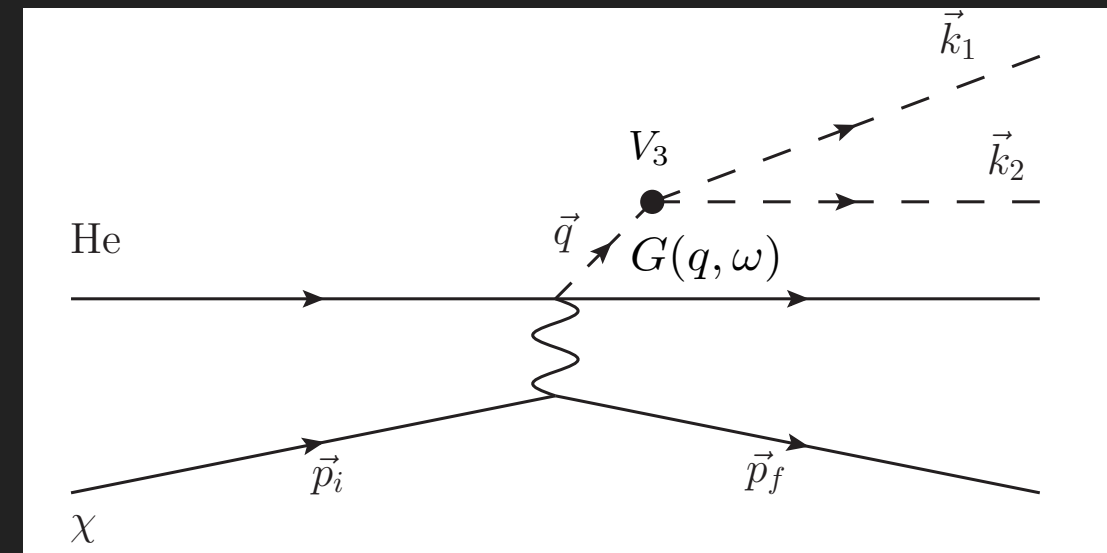
► Compute

$$(\vec{k}_1 \vec{k}_2 | H_3 | \vec{q}) = - \frac{(\vec{q} \cdot \vec{k}_1 U(k_1) + \vec{q} \cdot \vec{k}_2 U(k_2) + q^2 U(k_1) U(k_2))}{2m_{\text{He}} (S(q) S(k_1) S(k_2))^{1/2}}$$

$$G(q, \omega) \sim \frac{1}{\omega}$$

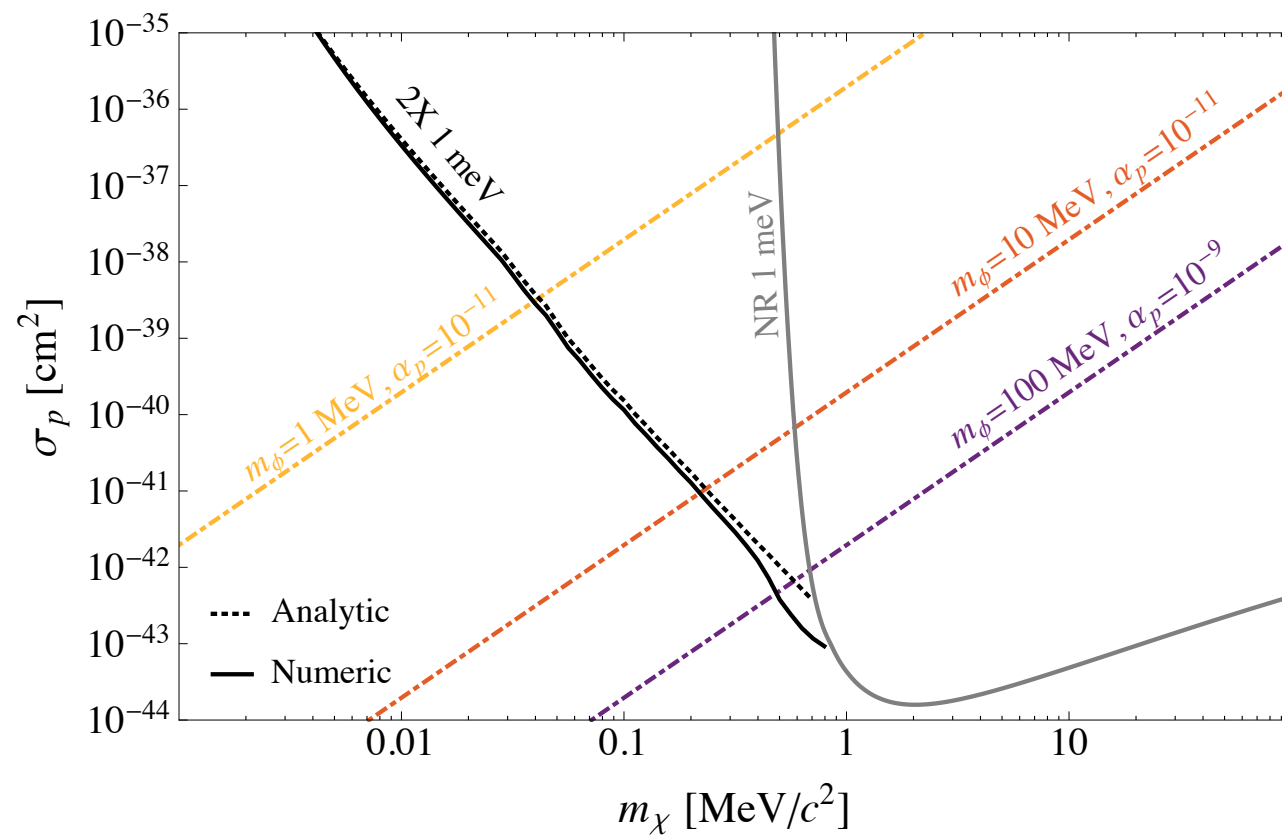
► Or, use simulation data

Campbell, Krotschek, Lichtenegger
Phys Rev B 91 184510

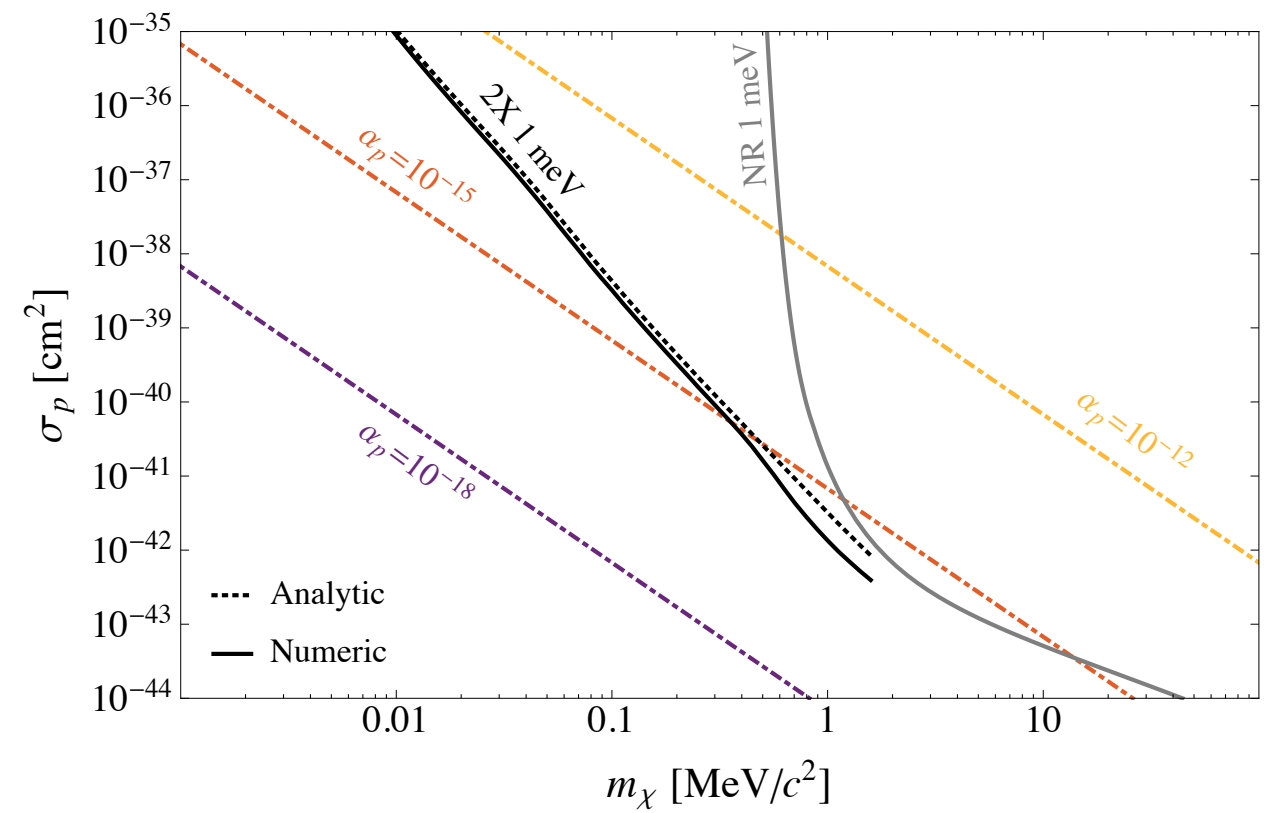


RESULTS

Sensitivity to DM via a Massive Mediator



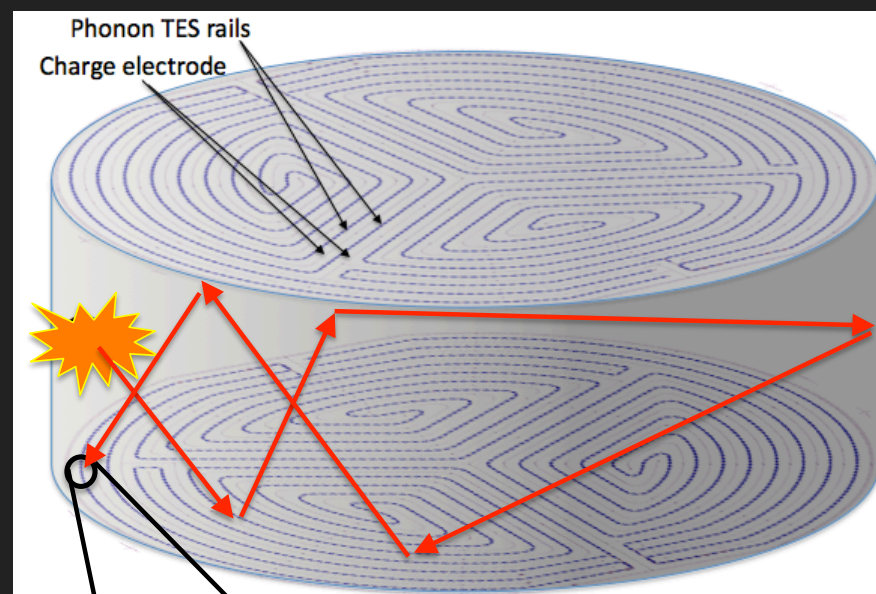
Sensitivity to DM via a Massless Mediator



Great potential!

ROAD FORWARD

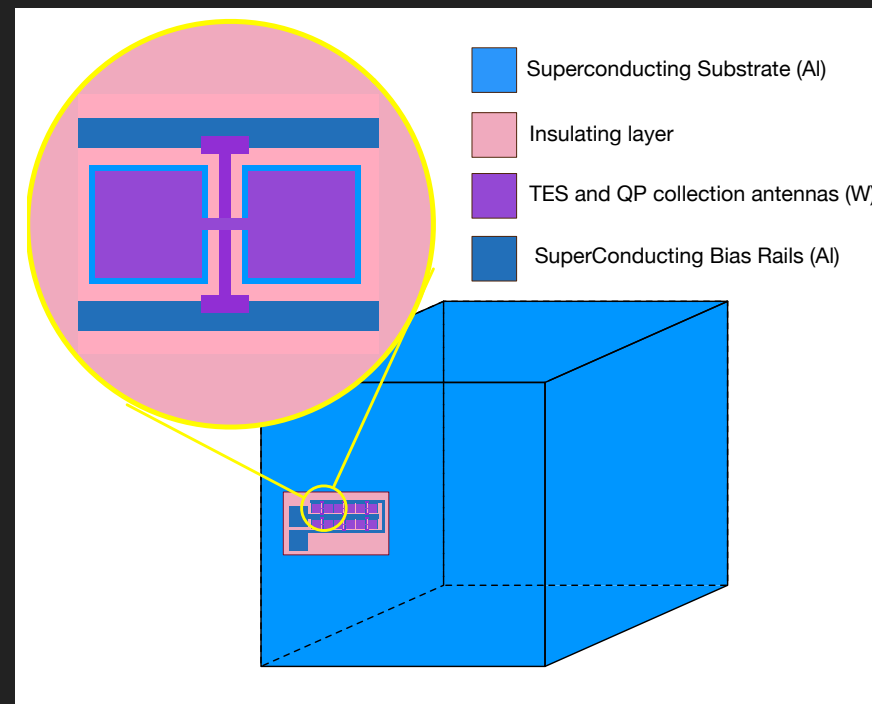
- Large part depends on better energy resolution sensors (TESs); TESs are portable to multiple targets



Semiconductors SuperCDMS

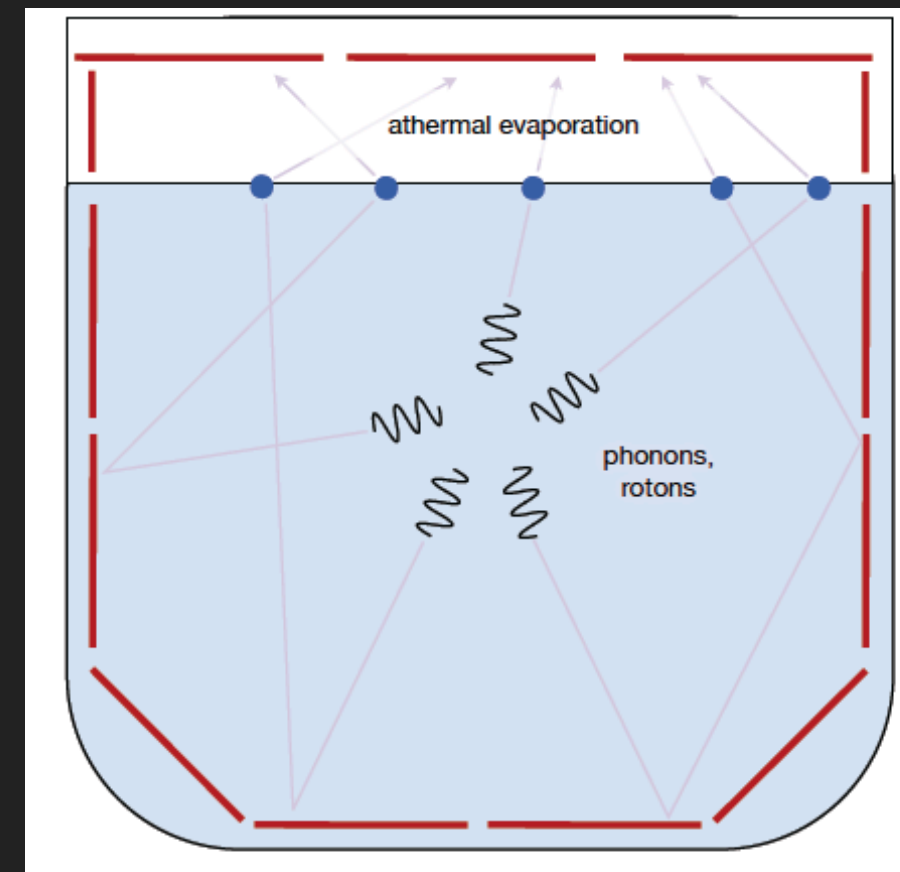
Current energy resolution: ~ 300 eV

Goal: ~ 1 eV



Superconductors

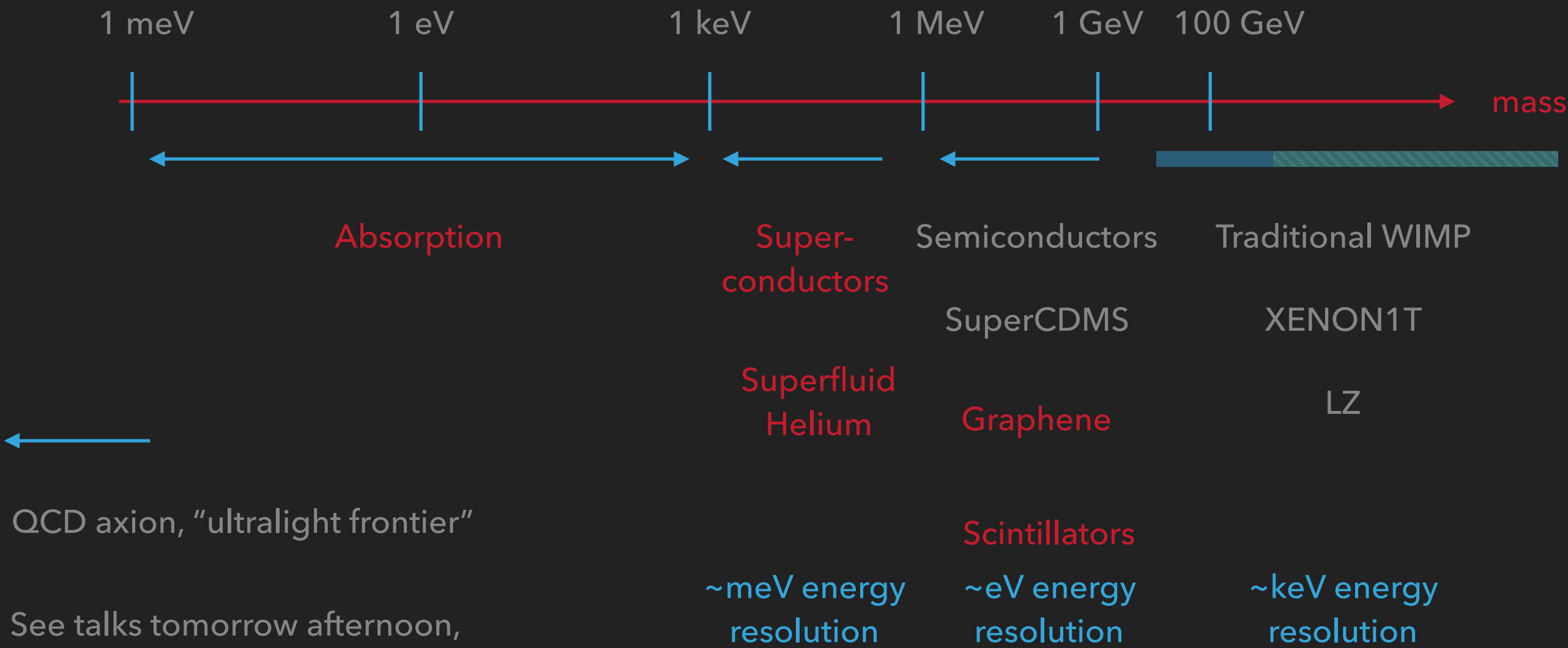
Goal: ~ 1 meV



Superfluid Helium

Goal: ~ 1 meV

ROAD FORWARD



ROAD FORWARD

- ▶ New ideas for dark matter detection!
- ▶ Moving beyond nuclear recoils into phases of matter crucial to access broader areas of DM parameter space
- ▶ Target diversity essential. What kinds of materials remain to be explored?

ROAD FORWARD

- ▶ Leverage progress in materials and condensed matter physics
- ▶ Realizing experimental program is 5-10+ years into future
- ▶ Every step of R&D for current direct detection experiments (particularly SuperCDMS) can be applied to new dark matter candidates
- ▶ Better energy resolution sensors portable between targets
- ▶ Nine orders of magnitude increased sensitivity in mass
- ▶ Long view necessary!

ROAD FORWARD

